RE-THINK THE STREETS:

AN EVALUATION OF GREEN STREET PRACTICES AS A METHOD TO ACHIEVE COMBINED SEWER SEPARATION

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To those who have allowed me to indulge in more than one sewer-related rant

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It certainly does take a village. Thank you all, we did it!

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LIST OF SYMBOLS AND ABBREVIATIONS

BMP	Best Management Practice
CF	Cubic Foot
CDA	Contributing Drainage Area
CFS	Cubic Feet per Second
CSA	Combined Sewer Area
CSO	Combined Sewer Overflow
CSS	Combined Sewer System
CWA	Clean Water Act
DWM	City of Atlanta Department of Watershed Management
EPA	United States Environmental Protection Agency
GDOT	Georgia Department of Transportation
GIS	Geographic Information System
GSI	Green Stormwater Infrastructure
GSMM	Georgia Stormwater Management Manual
LF	Linear Foot
NPDES	National Pollutant Discharge Elimination System
PSF	Per Square Foot
ROW	Right-of-Way
SCM	Stormwater Control Measure
SF	Square Foot
SPU	Seattle Public Utilities
WQ_v	Water Quality Volume

SUMMARY

Older cities across the United States have been grappling with how to mitigate stormwater for decades. The ongoing trend of land development coupled with the heightened frequency and intensity of storm events has necessitated costly infrastructure improvements that are short-sighted and fail to address the underlying cause of increased runoff. Green stormwater infrastructure (GSI) has recently emerged as a popular stormwater mitigation tool that mimics and restores the natural environment while providing the same functional benefits as conventional systems.

The purpose of this research is to evaluate the effectiveness of GSI in roadside applications (i.e., “Green Streets”) to reduce combined sewer dependency and provide an alternative solution to sewer separation. Typically, roadways reach the end of their design life after 40 years, at which point, they are fully reconstructed. Reconstruction provides an opportunity to re-imagine the right-of-way (ROW) and shift away from conventional drainage design. The Green Street Toolkit presented in this research provides a planning and design framework that can be utilized prior to reconstruction to integrate green infrastructure into the ROW, which has the potential to eliminate stormwater runoff from the combined sewer system along the reconstructed segment. The Toolkit is applied under three design storm scenarios to evaluate the feasibility of a green street approach for varying storm intensities. Although green streets may not eliminate combined sewer dependency in every case, this work shows their potential in removing a substantial amount of stormwater runoff from the combined sewer system while providing secondary benefits not offered by conventional infrastructure.

CHAPTER 1. INTRODUCTION

"Don't it always seem to go that you don't know what you got 'til it's gone

They paved paradise and put up a parking lot."

- Lyrics from Joni Mitchell's Big Yellow Taxi, 1970

The trend of urbanization in the United States has generally been regarded as positive, but while growing cities are a proxy for bustling economies and new opportunities, the resulting influx of development has resulted in changes to the physical environment that have outpaced the capabilities of existing infrastructure. As of 2020, it's estimated that over 83% of the U.S. population lives in urban areas, and by 2050, this percentage is expected to increase to 89% (Center for Sustainable Systems 2020). Construction of new buildings and roadways to accommodate population growth has resulted in major reductions of pervious surfaces, generating large volumes of runoff that are blindly handed off to city sewers. Sewers have long provided a convenient "out of sight, out of mind" approach to handing runoff, but as development density increases, frequent back-ups and local flooding have become commonplace. In cities with combined sewer systems where sanitary waste and stormwater flow within the same pipe, overwhelmed pipes are not only a flooding hazard, but a threat to public health.

Historically, once the runoff becomes too much to handle, cities have addressed the problem with what they thought was a silver bullet, combined sewer overflows (CSOs). During heavy rain events, CSOs intercept and store large quantities of runoff until treatment plants downstream have the capacity to treat the waste. Even the largest CSOs are prone to fail during some rain events, such as those with high intensity or long duration, forcing runoff to bypass treatment plants and discharge into local waterways. Engineers and city officials have started to reach the consensus that large-scale CSO projects are costly, disruptive, and unable to provide sufficient capacity long-term.

For the past 30 years, the United States Environmental Protection Agency (EPA) has been working with cities to address and eliminate CSO pollution. Combined sewer separation has emerged as the EPA's leading solution because it reduces the amount of volume in the system during a heavy rain event. However, combined sewers are mainly found in older, more developed cities, meaning a full overhaul of a combined system is not only physically challenging, but cost prohibitive. Recently, a handful of U.S. cities have turned to alternative approaches, calling on engineers to design and construct infrastructure that mimics the natural environment, commonly referred to as green infrastructure. Unlike CSOs, green stormwater infrastructure (GSI) is designed to mitigate runoff issues at the source by slowing the time of concentration (the time it takes for runoff to enter the system), reducing the peak volume, and filtering contaminants through infiltration.

While GSI has gained immense popularity over the past decade, conventional, or "gray" infrastructure remains the predominant method to control stormwater runoff for two reasons; first, engineers are reluctant to experiment with public works, and second, politicians hesitate to allocate their already limited budget toward projects with little precedent. Yet, over the last 100 years, as cities have continued to address stormwater runoff with tried-and-true gray infrastructure, the problem – much like the diameter of CSO pipes – continues to grow.

The time has come to move beyond conventional solutions and to start approaching public infrastructure as a comprehensive system with interdependent components. Even within the existing academic research, there is a natural tendency to study each type of infrastructure individually, rather than as a system with dependent interactions. This paper seeks to intertwine two fundamental pieces of civil infrastructure - roadways and sewers - to present an alternative method to sewer separation using green infrastructure.

The methodology presented in this research is in the form of a Green Street Toolkit which provides a process to incorporate green infrastructure into the roadway during the reconstruction cycle. Typically, roadways reach the end of their design life after 40 years, at which point they are fully reconstructed. Oftentimes, during reconstruction the entire right-of-way (ROW) is improved, which provides an opportunity to re-imagine the adjacent infrastructure – including roadway and stormwater drainage. The Green Street Toolkit provides a framework that can be utilized prior to reconstruction to integrate green infrastructure into the new design, which has the potential to remove stormwater runoff from the combined sewer system along the reconstructed segment. While green infrastructure is not an entirely new subset of civil engineering, programmatic integration into roadway reconstruction across large areas is rare. Thus, this research examines the potential a systematic green street approach has in alleviating, and possibly eliminating, the need for combined sewers over just one reconstruction cycle, i.e., 40 years.

The methodology acts as a planning analysis that helps bridge the gap between policy and implementation, and therefore the contribution this work makes to the field of civil engineering and, more specifically, green streets, is two-fold. On the policy side, the methodology is intended to inform the stormwater standard that should be enforced (i.e., how much runoff should be captured?). On the implementation side, it provides a standardized prescription for green street design that can be applied universally (i.e., the type of GSI that should be considered for a given roadway segment and the extent of roadway modifications necessary to install it). Although existing stormwater guides and manuals provide technical information on green infrastructure, they tend to be too general or too specific. For example, the National Association of City Transportation Officials (NACTO) provides several recommendations on how to incorporate stormwater mitigation into roadway design, but they stop short of providing quantitative analyses (i.e., how much runoff can a specific type of GSI store, how much does it need to store according to local rainfall data, and what is the projected physical impact to the roadway?). On the other hand, manuals such as the Georgia Stormwater Management Manual (GSMM) provides thorough documentation of quantitative methods, but is better suited for new, private development as opposed to retrofits or roadway applications. Thus, this work provides value because it collects pertinent information from relevant resources and synthesizes it to create a quantitative and qualitative planning methodology that specifically focuses on green streets.

The main case study presented in this research applies the Green Street Toolkit to the combined sewer area within the City of Atlanta under three storm scenarios with varying degrees of rainfall intensity. However, the methodology is intended to be replicable for any city that experiences combined sewer-related issues such as localized flooding, poor water quality, or frequent sewer overflows. Atlanta provides a unique lens with which to study the effectiveness of the Green Street Toolkit because the combined sewer area is located within densely populated, and many times, historic, areas. Furthermore, there has been a longstanding assumption that the remaining portion of the city's combined sewer system will never be separated due to budgetary constraints. Yet over the past 20 years, Atlanta has spent more than more than $2.5 billon to comply with CSO regulations and is on track to spend another $1.2 billion by 2030 (City of Atlanta DWM 2020c). Once the planned improvements are completed, there is still no guarantee that all CSO events will be eliminated. Unfortunately, physical and budgetary constraints related to sewer separation are not unique to the City of Atlanta, and a new approach to controlling stormwater is desperately needed across much of the US. The Green Street Toolkit methodology presented in this research has the potential to alter the way cities treat stormwater while creating infrastructure that serves as an asset, rather than a risk.

1.1 General Outline of Paper

This paper presents a toolkit that assesses existing roadway characteristics and proposes a suite of green infrastructure solutions to be applied during reconstruction that are most appropriate given the assumed existing conditions. CHAPTER 2 provides a summary of relevant literature, including an overview of the history of combined sewers and current best practices in green infrastructure. CHAPTER 3 presents the underlying methodology in creating the Green Street Toolkit. CHAPTER 4 applies the Toolkit to the main case study, the City of Atlanta, and is followed by an in-depth discussion of the case study analysis and results. Finally, CHAPTER 5 discusses opportunities for future work and improvements upon this research, as well as policy recommendations to aid in the planning, implementation, and maintenance of the Green Street Toolkit.

CHAPTER 2. BACKGROUND

This section presents a review of existing literature that was performed to understand the origins of sewer systems in the United States and the repercussions that stem from the decision to utilize combined versus separate sewer design. The shift from "gray" to "green" sewer design is also discussed, highlighting examples from U.S. cities that have recently adopted low impact design strategies to mitigate the negative effects of CSOs. The last portion of this section provides context for the City of Atlanta, including a brief history of the City's longstanding issues related to combined sewer overflows, a profile of the existing stormwater infrastructure, and the current planning initiatives that promote the implementation of green infrastructure.

2.1 Combined sewers vs. separate: How did we get here?

Water and sewer have long been used within the same engineering purview, but in the 19th century, while hundreds of cities across the US were busy planning and constructing water systems, not one was simultaneously planning a sewer system (Tarr 1979). Adequate water supply has been a facet of municipal infrastructure since the beginning of cities themselves, but when piped water became commonplace for individual residences, the familiar logic of "what comes in must go out" was overlooked. In fact, the first method of discharging waste hardly utilized pipes at all, and instead was comprised of a decentralized network of privy vault-cesspools. The elementary design consisted of a stone-lined hole in the ground that facilitated absorption of waste into the underlying soil. When a vault reached capacity, it was covered with dirt, abandoned, and replaced with a new vault nearby. Contamination was rampant, caused either by the infiltration of waste into groundwater, or from heavy rains that directed overflows to nearby gutters and ultimately, drinking water supplies.

Eventually, population growth and increased housing density generated such immense volumes of raw sewage that the privy vault-cesspool method went from a general nuisance to a public health hazard (Tarr 1979). By the mid-nineteenth century, city leaders began to recognize the benefits a well-planned network of sewers would provide. Not only would sewers offset the cost of maintaining the privy vault-cesspool system but improved sanitary conditions would decrease mortality rates and attract a larger share of population and industry growth than slower-adapting cities. The sanitation issue was compounded by the presence of unpaved streets, which resulted in poor drainage conditions and saturated soil laden with contaminants (Schultz and McShane 1978). Thus, cities were dealing with two issues at once – wastewater *and* stormwater. Rather conveniently, there was one solution – sewers.

From 1860 to 1890, major cities across the US underwent massive public infrastructure transformations due to the addition of sewers and paved roadways. The decision regarding whether sewers should be constructed as separate systems – wastewater in one pipe and stormwater in the other – versus combined systems was dictated by three main factors: there was a lack of European or American precedent for a successful separate system, a reluctancy from engineers to experiment with large capital works, and the reality that combined sewer systems were more economical than separate systems (Tarr 1979). Colonel George E. Waring Jr, a prominent sanitarian, was the first to promote separate sewer systems in the United States by arguing that human waste needed to be removed expeditiously to eliminate the formation of sewer gas that could become toxic and exacerbate unsanitary conditions (Tarr 1979). In 1879, Waring designed a sanitary-only sewer system for the city of Memphis, TN, which had been ravaged by yellow fever - a common side-effect of unsanitary conditions. Although there were essentially no provisions for the removal of stormwater, Waring's sanitary-only design proved successful in two ways; it greatly reduced the unsanitary conditions that had caused over 5,000 deaths in the two years prior and it had done so at a cost that was comparable to combined systems (Tarr 1979).

In 1881, a report submitted to the National Board of Health by sanitary engineer Rudolph Hering would provide the final say on which design was superior. Hering concluded that neither design was more sanitary than the other, and instead, the choice should be made using a rational planning method that weighed factors such as cost of construction, maintenance, and the overall needs of the local area. In general, combined sewers were more suitable for larger, more developed cities that had pressing needs to address both wastewater removal and street drainage via underground removal, while separate sewers were more fitting for smaller cities where household waste was the primary concern (Tarr 1979). Hering's report became so widely accepted by engineers that by 1909 constructed miles of combined sewers outnumbered sanitary-only sewers by a ratio of 7:1 in cities with over 100,000 inhabitants (Tarr 1979).

While Hering's conclusion that the *conveyance* of sewage within combined versus separate pipes did not differ in terms of sanitation was generally correct, he grossly overlooked the condition that would be created at the ultimate outlet of each system. The underlying theory at the time was that sewers could safely dispose of any amount of sewage in nearby waterways because running water had the ability to purify itself. However, at the turn of the 19th century, communities who found themselves downstream from cities with large combined sewer systems experienced yet another round of waterborne diseases (Tarr et al. 1984). On the other hand, the lack of dilution in separate systems led to the construction of sewage treatment plants, and cities that had constructed separate systems did not experience the same widespread sanitation issues. Thus, the dilution theory was replaced with the notion that water could easily become contaminated if overwhelmed by large influxes of sewage, especially when left untreated. While it was too late for developed cities to separate their entire combined sewer system, many began construction of large sewer treatment plants at major discharge points to thwart the ongoing sanitation issue.

The combined sewer systems and their associated treatment plants that were constructed around the turn of the century largely make up the backbone of today's infrastructure in most older cities. As cities continued to grow and develop, so did the square footage of impervious surfaces. Increasing amounts of pavement resulted in more runoff, which in turn required additional capacity from the combined sewer systems. The most economical solution to provide additional capacity was to construct large-diameter pipes, or combined sewer overflows (CSOs), and connect them to the existing sewer system. CSOs are designed to capture and store excess runoff until it can be treated at the wastewater treatment plant (although some solely serve the purpose of conveyance during an overflow) and immediately release runoff into nearby streams and rivers (Moffa 1997). In the last half of the 20th century, CSOs have experienced their own share of capacity issues during rain events with high intensity or prolonged duration, a trend that is expected to increase due to climate change and ongoing development.

The development of policy related to water quality and stormwater discharge has followed a similar timeline to that of sewer systems and CSOs. The Federal Water Pollution Control Amendments of 1972, commonly known as the Clean Water Act (CWA), was the first policy to establish a baseline framework that addressed and enforced acceptable water quality on a national level (Flatt 1997). Previously, policy had been left up to the individual state, but environmental issues tend to follow a concept known as "the race to the bottom", where states value short-term economic success over long-term well-being of a community, and therefore do not enforce regulations that properly protect human health and safety (Flatt 1997). The goal of the CWA was to make waters of the US "swimmable and fishable" through the regulation of point source pollution – or pollution that was being discharged by a known entity at a specific location. Industrial pollution and urban populations were the two prime targets of the CWA, as both were experiencing substantial growth, yet remained heavily unregulated. For urban populations, this meant the regulation of publicly owned sewage treatment plants and CSO facilities (Moffa 1997).

The primary mechanism by which the CWA aimed to regulate treatment plants and CSOs was through the National Pollutant Discharge Elimination System (NPDES). The NPDES permitting system shifted the responsibility of testing and monitoring to the discharger, who then had the responsibility of reporting violations directly back to the appropriate state agency or the EPA. Addressing pollution at the individual permit level allowed several things to happen. First, it allowed treatment plants to develop and monitor their own programs based on EPA standards, which meant they could tailor their permit conditions to the treatment technology that was available. Second, any permit holders that were not in compliance were held liable, meaning the EPA could bring a civil action in federal court and administer fines directly to the discharger. The goals of the NPDES were to establish a working relationship between the EPA at the federal level and environmental organizations at the state level (Flatt 1997). Permits were initially issued for a five-year period and renewed thereafter. This permitting system still serves as the main mechanism for compliance and enforcement for treatment plants and CSO facilities.

In addition to the NPDES, the EPA also published a National CSO Control Strategy in 1994 to specifically address pollution caused by permit holders that operate CSOs. There are three main objectives of the policy; prevent dry weather CSOs, facilitate CWA compliance of all wet weather CSOs, and minimize CSO impact on water quality, human health, and the environment (Sader 1994). Although the CWA also states these objectives, the goal of the CSO Control Strategy is to provide additional flexibility in the compliance process by considering the most cost-effective solution, which may still result in violations, albeit less frequently (Sader 1994). The policy goes on to define a set of minimum controls for CSO permittees which have since been included into NPDES permit stipulations. The last component of the policy is guidance for long-term CSO planning that provides a framework for bringing all facilities into compliance of the CWA (Sader 1994). Even though cities have continually worked to update their sewer facilities to meet the conditions of their NPDES permits and CWA water quality standards, the timeline to achieve compliance remains unclear. The issue of compliance has been further complicated by continued population growth, changing climactic conditions, and the massive capital required to implement new controls. Meeting the water quality standards put forth by the CWA has been one of the most significant challenges for public works operators since the

Act’s inception in 1972, and although additional policies have worked to address pollution caused by CSOs and water treatment plants, compliance continues to be an ongoing battle.

As of 2005, it is estimated that 40 million people in 32 states live in cities that continue to utilize combined sewer systems (EHP, 2005). CSOs, which supplement nearly every combined sewer system, produce an estimated 850 billion gallons of untreated wastewater that flows into US waterways annually (EHP, 2005). Although combined sewer systems have received continual upgrades since their conception, CSO events and local flooding are recurring issues for most US cities. Limited municipal budgets compound the issue and create a tug-of-war between infrastructure investments, leaving cities with no other option than to fix what is necessary and defer all other maintenance until a later date. Cities have been left with hefty price tags for sewer system improvements that still do not ensure compliance with policy that was established over 50 years ago, yet at this point, there is no other option than to leave the combined system in place, and in many cases, expand upon it. However, history has shown that there are few instances in which there is a pipe big enough to appropriately store and treat the increasing amount of stormwater in a drainage network. Rather than repeat the past, engineers and public works operators have been tasked with finding alternative solutions that are flexible in the long-term and less capital-intensive in the short term. One of the leading solutions has started to gain steam in the slow-moving profession of civil engineering: green stormwater infrastructure.

2.2 Green Stormwater Infrastructure: A solution to sewer separation?

Green stormwater infrastructure (GSI) is defined extensively throughout existing literature, but a concise description is eloquently worded by Finewood (2016) as "infrastructure designed to control water at the source (as opposed to sending it into the sewer system) by utilizing scaled systems that mimic ecological processes." (1001). Put simply, GSI utilizes soil and vegetation, rather than hard pipe, to accomplish two goals of stormwater management: reduced runoff quantity and improved water quality. When runoff percolates through vegetation and soil, some (or all) of the stormwater is retained and the volume of discharge is reduced. This process also decreases the rate at which stormwater is discharged, freeing up much-needed capacity within the network during a rain event. Lastly, as runoff moves through the GSI facility, the soil and vegetation act as a filter, removing harmful contaminants from the stormwater, which in turn, improves the overall quality of water that is discharged.

There are a myriad of other terms that are often used in conjunction with GSI, such as stormwater control measures (SCMs) that refer to both green and gray infrastructure, or best management practices (BMPs). BMPs, as defined by Bell et al. (2019), refer to a subset of infrastructure that are installed in developed areas with the purpose of "retaining, reducing, or improving the quality of stormwater runoff." (3). Emerging literature cautions against the exact classification of SCMs because the solution for any given scenario often contains a combination of both green and gray infrastructure technologies. Rather than strict definitions, SCMs exist on a "gray - green stormwater infrastructure continuum" (1) that weighs factors such as construction materials, drainage area, and dominant hydrological and water quality processes as shown in Figure 1 (Bell et al. 2019).

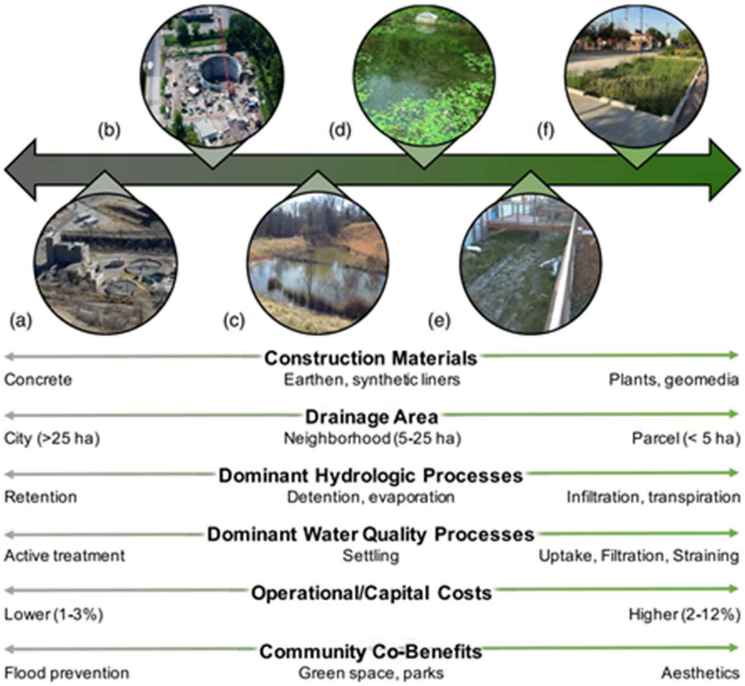


Fig 2. Gray-green stormwater infrastructure continuum. Continuum shows how decision-making criteria (materials, drainage area, hydrologic and water quality processes, life cycle cost characteristics, and potential community cobenefits) vary between gray and green endpoints of stormwater control measure design. Simultaneous display of all these criteria is beneficial for holistic stormwater management planning. Images: (a) Coors Wastewater Treatment Plant in Golden, Colorado; (b) Lower Harbor Brook CSO Storage Facility in Syracuse, New York (image courtesy of Onondaga County Save the Rain program at savetherain.us); (c) detention pond near Charlotte, North Carolina; (d) constructed wetland in Charlotte, North Carolina; (e) infiltration trench in Denver; and (f) bioretention basin in Lafayette, Indiana. [Images (a and c–f) by authors.]

Figure 1 – The gray-green infrastructure continuum
(Bell et al. 2019)

The classification of GSI is further complicated by the wide variety of naming conventions that are employed across the United States. For example, stormwater planters may also be referred to as rain gardens, or bioswales as vegetated swales. Moreover, two stormwater planters installed at separate locations within the same city may utilize different technologies – one relying on infiltration, while the other utilizes detention. Table 1 provides baseline descriptions for all GSI solutions that will be discussed throughout this paper. To ensure consistent terminology, the green infrastructure types are aligned with local and regional resources, including the 2016 edition of the Georgia Stormwater Management Manual, or “The Blue Book”, The City of Atlanta Department of Watershed Management, and The Atlanta Regional Commission. It should be noted that the list of GSI devices is not exhaustive, and only includes solutions that are suitable for use within the public ROW, which most often consists of roadways, sidewalks, and linear landscaped areas. More details on each solution are provided in Chapter 4.

Table 1 – Green infrastructure definitions

Green Stormwater Infrastructure (GSI)	Description
Bioretention Area	Bioretention areas are shallow excavations that utilize engineered soils and hydro- and hydric-tolerant vegetation to capture and treat stormwater runoff. Their primary hydrological functions include retention or detention depending on the infiltration rate of the underlying soils. Bioretention areas vary in shape and size and can treat runoff from large or small areas. They may be enclosed within a curb or may accept sheet flow directly from adjacent areas.
Bioswale	Bioswales are shallow, linear excavations that primarily convey stormwater runoff to nearby storm sewers or other types of GSI. They can be further classified as wet or dry depending on the depth of the underlying water table. A shallow water table constitutes a wet swale, while a deeper water table allows for a dry swale. They may also be designed to temporarily detain or permanently retain small runoff volumes. Bioswales vary in size but are an optimal candidate for GSI in the right-of-way because of their linear shape.
Stormwater Planter or Curb Extension	Stormwater planters are like bioretention areas but are typically more appropriate for dense urban settings. They utilize engineered soils and vegetation to treat and store runoff from small drainage areas and may be designed for detention or retention. Stormwater planters vary in both width and length, and may be aligned with the existing curb and gutter line (i.e. stormwater planter) or may be extended into the existing roadway pavement (i.e. curb extension).
Infiltration Trench	Infiltration trenches are deep stone-lined excavations that intercept sheet flow from adjacent areas. Typically, infiltration trenches utilize retention, but poor draining soils may require an underdrain and some element of detention. Regardless, an infiltration trench must be designed to drain within a specific time period, most often 24-72 hours. Infiltration trenches are typically linear, but vary in length, and may be constructed much deeper than other types of GSI (up to 12 feet deep) depending on the presence of underlying infrastructure.
Subsurface Infiltration and Detention	Subsurface infiltration and detention systems are deep excavations that utilize a combination of stone and plastic or concrete chambers to maximize void space below-grade, thus increasing potential runoff storage. Runoff enters the systems through drainage structures, which direct the flow to the system where it fills up like a bathtub. Subsurface systems typically rely on a combination of detention and retention due to the large volume of water they can capture. Subsurface detention systems vary in size, but are typically rectangular in shape, although linear systems are possible. Significant clearance from other utilities makes installation of these systems in the right-of-way a challenge.
Permeable Pavement	Permeable pavement systems refer to permeable pavers, porous concrete, or porous asphalt. Pavement systems capture and utilize rapid infiltration through void space to quickly clear stormwater from the surface. Permeable pavements can replace conventional pavement in low-volume areas and are only designed to capture the runoff generated within its own footprint.

The advent of GSI into mainstream civil engineering practice is a relatively recent advance, and until recently, projects have predominately been proposed within new or existing green areas and private development. In the past ten years the attention has shifted to the public realm, more specifically, the roadways and vast expanses of pavement that now make up many urban cores. The integration of GSI into linear roadway projects, or "green street" design, is an emerging concept within civil engineering that takes a more holistic planning and design approach than conventional roadway or stormwater projects. Peters et al. (2008) claims that green streets can do more than just manage stormwater, as they also have the potential to enhance mobility, improve social spaces, and promote biodiversity.

One of the first successful green street programs was initiated in 1999 by Seattle Public Utilities' (SPU) where the ultimate goal was to reduce stormwater runoff into the Puget Sound through the use of natural drainage systems (Tackett 2008). SPU initially completed five pilot projects that ranged in scale from block-level to neighborhood-wide where they employed a variety of GSI techniques to improve water quality and reduce runoff quantity. SPUs' High Point project utilizes a combination of bioretention, conveyance swales, pervious pavement, rain gardens, and tree preservation, and is deemed one of the largest urban applications of green streets in the US (Tackett 2008). The project achieves several goals, including better management of local flooding, improved water quality, decreased stormwater flow rates, and reduced stormwater discharge volume. Tacket (2008) also mentions co-benefits of the project, including increased pedestrian safety and enhanced aesthetics. Seattle's natural drainage systems program also highlighted the importance of interdepartmental coordination through the bridging of design standards created by SPU and the Seattle Department of Transportation (Tackett 2008). The standards provided the foundation for all five project designs, and more importantly, achieved common goals from multiple departments.

While Seattle provided one of the earliest examples of a green streets program, other cities throughout the US have also initiated programs to incorporate GSI into linear construction. Los Angeles, a city with over 6,500 miles of streets and 10,000 miles of sidewalk, has focused on implementation of smaller projects over a broad scale (Susilo and Abe 2010). In addition to conventional benefits, the city experienced a plethora of co-benefits, such as renewed community pride and positive public perception of urban areas, both of which have contributed to economic activity and growth. Although the results in Los Angeles have been generally positive, Susilo and Abe (2010) highlight several lessons learned in that can inform future applications. For example, engineering constraints, including poor infiltration capacity, polluted soils, the need for overflow systems, and extensive maintenance, are commonly cited issues in Los Angeles. Such issues will likely exist for any urban application throughout the US, and thus should be anticipated for future green street projects. Project activities such as soil testing, site-sensitive engineering design, thoughtful plant selection, and ongoing monitoring all work to maximize the potential of green street applications.

Portland, OR, a longtime frontrunner in GSI applications, provides one of the best examples of a programmatic approach to green streets through the development of their "Green Street Toolbox" (City of Portland 2020). The Green Street Toolbox was introduced in 2005 as a cross-bureau effort between Portland's Bureau of Environmental Services, the Portland DOT, and the Department of City Planning, and has been utilized for over 500 green street facilities across the city (City of Portland 2020). The toolbox offers a variety of design solutions that reflect the myriad of existing conditions that are often found in urban environments. The least complex design is the “simple green street”, which utilizes a trapezoidal-shaped, longitudinal planter placed between the existing curb and sidewalk. The toolbox also includes other standard details for check dams, curb extensions, vegetated planters, inlet design, and rain gardens (Elkin 2008). Each detail is accompanied by minimum depths, standard dimensions, estimated construction cost, and a list of considerations for implementation, such as how to maintain bicycle or on-street parking facilities, or what solutions work best for streets with high traffic volumes or steep grades. The city stresses the importance of “understanding the difference between cost, benefits, function, and aesthetic” (2) for every application to maximize the benefits of green streets, and the inherent flexibility of the toolbox allows greater opportunity for widespread implementation. Portland also cites both direct and indirect benefits that have arisen from their green street projects. Direct benefits include environmental improvements such as recharge of groundwater, rehabilitation of soils, and filtering of pollutants, while indirect benefits consist of socioeconomic improvements like general neighborhood beautification and increased property values (Elkin 2008).

Although green streets are a relatively new concept within GSI, the practice has been around for nearly two decades and has proven itself to be one of the most economical solutions to mitigating CSO impacts through the reduction of stormwater runoff and filtration of harmful pollutants. The holistic planning and design approach that green streets utilize has created positive environmental and social externalities that have contributed to widespread acceptance of the use and purpose of GSI within the ROW. Ongoing interdepartmental cooperation was also a common theme amongst every successful green street program, highlighting the ubiquity of common goals that already exist between departments, and stressing the importance of city departments working together to strike the right balance between engineering, economics, and the environment.

Resources for green street policy, construction, and maintenance have been made increasingly available thanks to public entities like SPO and the City of Portland, but a lack of technical planning guidance has created a disconnect between the establishment of green infrastructure policies and the execution of projects. This research seeks to bridge this gap by providing a data-driven planning process that uses an inventory of existing conditions to prescribe multiple design scenarios in which GSI can be integrated into roadway reconstruction projects. Executing this analysis throughout a combined sewer service area before a programmatic green streets policy is established helps illustrate the physical feasibility of a policy and informs the necessary performance standards for GSI. The methodology used in this research equips engineers and designers with a framework to determine the types of GSI that should be considered for a particular project, as well as the roadway modifications necessary to achieve the required performance standards. Complementary policy and design lay the foundation for a successful green street program and the Green Street Toolkit aims to bridge the technical information gap that currently exists.

CHAPTER 3. METHODOLOGY

This section presents a methodology to be utilized by a public entity to reduce CSO dependency in the interim and move towards sewer separation long-term using a GSI. The methodology is in the form of a Green Street Toolkit that can be applied systematically to linear construction projects. First, an existing conditions assessment is performed to define characteristics of the roadways within the combined sewer area. Physical characteristics such as roadway width, number of lanes, and type of lanes (e.g., driving versus parking) are gathered for each segment to determine the space available for GSI in the ROW under several reconstruction scenarios. Next, stormwater calculations are performed for each segment for three design storms to assess the volume of runoff that must be captured using GSI. After existing conditions are assessed and runoff calculations are performed, a suite of appropriate GSI solutions and associated reconstruction scenario is determined through an iterative process.

The Toolkit maximizes project feasibility by providing a ranking of GSI solutions for a given segment that range from the most preferred solution to the least. Rankings will be dictated by criteria such as storage capacity, construction cost, maintenance frequency, and other ancillary benefits or co-benefits. The Toolkit provides a foundation for a green street design approach but will function best if periodically updated by the local jurisdiction to incorporate planning, construction, and maintenance data from completed GSI projects.

The methodology presented in this section is intended to be a process undertaken at the planning-level of a project. Once potential projects are identified, additional steps such as detailed planning (i.e., land acquisition, financing, etc.), engineering design, and maintenance scheduling must be carried out by the project team. While the Toolkit provides a crucial first step in reducing combined sewer dependency by eliminating runoff from the ROW, future work to separate the system will be required. More information on ultimate separation can be found in Section 4.6.3.

3.1 Existing Conditions Assessment

The existing conditions assessment provides a detailed snapshot of roadway characteristics present within the study area. Figure 2, below, provides a general overview of the process for performing the assessment and lists the information that should be retrieved during each step of the process. Most of the data required for this analysis is public information and can be retrieved by the local governing jurisdiction. In many cases, city ROW data is publicly available online. Free mapping software, such as Google Earth, can also be used to acquire much of the data if it is not readily available from the jurisdiction. Once data is retrieved, it is recommended that a geographical information software (GIS) is used to compile the information in a geographic database to aid in the analysis outlined later in this section. The following subsections discuss each step of the existing conditions assessment in detail and the specific data that is required within each part of the process.

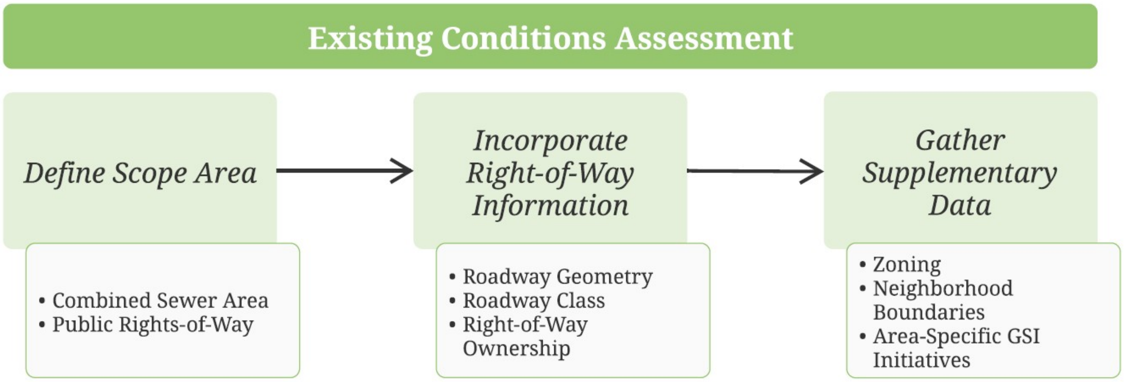


Figure 2 – Existing conditions assessment process

3.1.1 Define Study Area

The first step in the existing conditions analysis is to define the study area. The boundaries of the study area coincide with the boundaries of the combined sewer area (CSA). The CSA includes any land where stormwater is discharged into the combined sewer system (CSS) for collection and treatment. Since this analysis is concerned with the application of green stormwater infrastructure (GSI) for roadways, information regarding public rights-of-way, specifically those that include roadways, should also be incorporated. Interstates and major freeways should be removed from the dataset because these roadway types have significantly different standards regarding drainage, so many of the stormwater control measures proposed in this analysis would not be appropriate for such applications. The study area is then defined as any public ROW that contains a surface roadway and coincides with the CSA.

3.1.2 Incorporate Right-of-Way Information

After the study area is defined, ROW characteristics are incorporated into the dataset, including geometry, functional roadway classification, and ownership. Continuous stretches of ROW are broken into smaller segments to make runoff and design calculations more manageable. Ideally, segments should correspond with local drainage areas, meaning each segment represents an area that drains to a single point within the CSA – usually a drainage structure. In this analysis, drainage areas are unknown, so segments are broken into 500-foot lengths within the study area.

Next, geometric variables associated with each ROW segment are incorporated into the dataset. Variables include segment length, ROW width, roadway width, number of lanes, and type of lanes (i.e., driving, parking, or cycling). While this is not an exhaustive list of geometric characteristics, these variables represent the required criteria for this analysis. The functional classification of the roadway within each ROW segment is also incorporated. This analysis utilizes the functional classification system defined by the Federal Highway Administration (FHWA), which uses a set of criteria to determine the type of service a roadway provides. Examples of FHWA functional classification criteria include physical aspects of the road (e.g. lane width), speed limits, daily usage, and number of access points (FHWA 2000). In this analysis, functional classifications fall into one of three categories: arterial, collector, or local, and will be used to determine which types of GSI are appropriate for a given segment.

Roadway jurisdiction, or ownership, is the final piece of information that must be associated with each ROW segment. In urban scenarios, roadway ownership is likely to fall under a variety of jurisdictions, such as local (city, town, etc.), county, or state. Roadway jurisdiction governs almost every aspect of project compliance, including permit requirements, design standards, and construction specifications. Ideally, all jurisdictions will come to an agreement on the standards and specifications that will be used for GSI to ensure continuity across a single urban area. Moreover, many cities may have roadways that fall under one jurisdiction, while the underlying utilities fall under another. Thus, not only should standards for GSI surface treatments be coordinate, or at least complementary, but some level of cooperation will be required where ownership differs above-ground versus below-ground. Since GSI is a relatively new subset of civil engineering, city agencies typically allow more flexibility in design requirements. Oftentimes, agencies allow slight variation or exemption from design elements if the proper due diligence was performed during the planning and design stages.

3.1.3 Gather Supplementary Data

In addition to the quantitative data gathered in the previous section, there are several pieces of qualitative data that may prove useful when proposing GSI throughout large urban areas. Zoning, neighborhood boundaries, and local GSI requirements should be associated with each ROW segment when available. This information promotes context-oriented designs that consider the desired character of an area in addition to its physical attributes. Boundaries for zoning and neighborhoods are typically found within a city's comprehensive plan and may be published in GIS format by the local planning department. Zoning classifications typically dictate some qualitative aspects of a project, such as minimum sidewalk widths or landscape buffers, but they also define the principle use of an area (e.g., residential, commercial, industrial). Knowledge of existing and proposed zoning classifications can lead to more site-specific GSI applications. For example, a residential area might be more appropriate for “greener” GSI that contains abundant vegetation and offers aesthetic enhancements, whereas an industrial area might be better suited for “grayer” GSI that requires less maintenance and has a longer design life.

While zoning classifications provide a microscopic description of an area, neighborhood boundaries describe the area on a broader scale. Neighborhood boundaries outline the existing and desired character of each segment in the context of the surrounding area. For example, streets in dense commercial areas like midtown or downtown may require additional sidewalk space or roadway capacity, which would require a different suite of proposed GSI relative to a neighborhood that primarily contains residential streets. Grouping segments by neighborhood also allows for GSI planning on a larger level, which may be necessary for streets that lack capacity to capture runoff from larger storms within their individual segment limits. Furthermore, neighborhood character is less likely to change overtime, which is a departure from zoning classifications that may change frequently. Long-term green street projects will be most successful if using qualitative data such as zoning classifications and neighborhood boundaries to appropriately match GSI to each ROW segment.

3.2 Runoff Calculations

Once the dataset is complete, total runoff is calculated to determine the quantity of water that must be captured and treated through GSI. Three sets of calculations are performed per segment, and each calculation assesses a varied degree of storm scenarios. The first scenario calculates the water quality volume defined by Volume 2 of the 2016

Georgia Stormwater Management Manual (GSMM), which equates to the first 1.2” of rainfall that falls on a site (Atlanta Regional Commission 2016). The second storm scenario represents the runoff generated from a 25-year storm; a common flood control volume associated with many state design standards (US EPA 2011). The third scenario models the runoff generated from a 100-year storm. It is important to note that only roadway runoff, not sidewalk runoff, is accounted for due to a lack of data regarding sidewalk area. Although this is not ideal, the area of the adjacent sidewalk is negligible compared to the area of the roadway when assessing contributing drainage area.

3.2.1 Water Quality Treatment Volume Scenario

The base scenario examines the runoff and required storage for a rainfall depth of 1.2”, which represents approximately 85% of storms that occur throughout Georgia each year (Atlanta Regional Commission 2016). The water quality treatment volume (WQ_v) is GSMM’s minimum recommended requirement for stormwater runoff capture and is intended to capture smaller, more frequent storms. While the volume reduction from capturing the first 1.2” of runoff is significant, the main goal of capturing and treating the WQ_v is to improve local water quality by reducing the number of pollutants entering local waterways after a storm. The value of 1.2” is the average rainfall that occurs throughout Georgia for an 85th percentile storm event, and this depth still slightly exceeds local stormwater management requirements. The City of Atlanta stormwater management ordinance requires all new development (not including roadways) to capture and treat the first 1.0” of rainfall that falls on a site using GSI (City of Atlanta 2020). However, the GSMM merely suggests using better site practices to capture the WQ_v, which can include conventional stormwater mitigation practices under the gray infrastructure umbrella.

Therefore, this scenario represents a conservative combination of two local requirements: GSMM’s requirement that the first 1.2” of runoff is captured on a new development, and City of Atlanta’s requirement of using GSI as the primary stormwater mitigation method. The GSMM’s equation for WQ_v is:

$$WQ_V = \frac{1.2R_vA}{12} \tag{1}$$

where:
WQ_V = water quality volume (CF)
R_v = 0.05+ 0.009(I) where I equals percent impervious cover
A = site area (SF)

When applying this equation to a paved roadway, *I* is equal to 100, meaning 100% of the study area is assumed to be impervious. The square footage of each segment’s area (*A*) is calculated by multiplying the length of a given segment by the roadway width of that segment. The calculation is applied to every segment within the scope area, resulting in segment-specific runoff volumes per the ROW characteristics gathered in the existing conditions assessment. This calculation is carried out in the next section for the Atlanta case study.

3.2.2 25-Year, 24-Hour Storm Scenario

The second scenario examines the runoff volume generated by a 25-year, 24-hour storm event, or a storm that has a four percent (4%) likelihood of occurring within any given year. The runoff calculations performed for this storm follow the Soil Conservation Service NRCS TR-55 hydrologic method. All equations presented in this section were retrieved from Part 630 of the National Engineering Handbook (NRCS 2004). Designing for the 25-year storm is a common standard for communities across the US and a stated goal of the City of Atlanta Department of Watershed Management for GSI (Rutherford 2020). The second scenario is intended to provide an intermediate example of the effort required to provide GSI that can capture and treat larger storms while maintaining a reasonable level of physical feasibility.

The NRCS TR-55 method is generally recommended for sites that are smaller than 2000 acres and is primarily used for estimating peak flows and hydrographs for design applications (Atlanta Regional Commission 2016) . Since this planning-level analysis is performed over a large area with several unknowns, only the direct runoff for each segment is calculated for the pre-development condition. In a true design scenario, additional calculations would need to be performed for each individual segment to determine peak inflow rates and allowable discharge, which would ultimately dictate the design of each individual SCM. The calculations performed represent the pre-development condition only (i.e., the existing conditions), resulting in a more conservative runoff volume that must be stored by GSI. In a typical project, the post-development condition usually generates more runoff than the pre-development condition due to the addition of impervious surfaces (e.g., new sidewalks or buildings). The green streets projects proposed in this research, however, either maintain or decrease impervious area from the pre-development to post-development condition. Therefore, in contrast to a typical project, the pre-development condition yields the most conservative estimate for runoff volume. The steps for calculations are outlined below:

3.2.2.1 Step 1: Determine the amount of rainfall (*P*) generated by the 25-Year, 24-Hour storm event

Accumulated rainfall (P) is retrieved from rainfall intensity tables which are typically published by a state's environmental agency. If no such tables exist, the National Oceanic and Atmospheric Administration also publishes this data, albeit with slightly different intensity values since rainfall is dependent on agency-specific rain gauge locations. In this analysis, rainfall data was retrieved from the Georgia Environmental Protection Division. For a 25-year, 24-hour storm, rainfall intensity (i) in inches per hour is retrieved from the appropriate table, then P is calculated using the following equation:

$$P = i\frac{in}{hr} x\ 24\ hrs \qquad (2)$$

3.2.2.2 Step 2: Determine the runoff curve number (*CN*) for the development site (Pre-Development Condition)

The runoff curve number (*CN*) represents the potential runoff of a specified area (Atlanta Regional Commission 2016). A high runoff curve number indicates an area has more runoff potential and is more impervious, whereas a low number indicates an area has less runoff potential. Typically, runoff curve numbers vary depending on the permeability of the underlying soil, but in the case of paved roadways, the *CN* is 98, regardless of soil type (Appendix B). Therefore;

$$CN = 98$$

3.2.2.3 Step 3: Determine the initial abstraction (I_a) and compute stormwater runoff volume (Q) for the 25-Year, 24-Hour storm (Pre-Development Condition)

The TR-55 rainfall-runoff equation relates rainfall (*P*) calculated in Step 1 to runoff (*Q*) and is used for 24-hour storm calculations. The equation is as follows:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{3}$$

where:
P = accumulated rainfall (in) per Step 1 calculations
I_a = initial abstraction. The initial abstraction accounts of initial losses of runoff due to processes such as evaporation or infiltration.
S = potential maximum soil retention (in). S is calculated using the curve number (*CN*) found in step 2, and is also empirically related to I_a.

$$S = \frac{1000}{CN} - 10 \tag{4}$$

Then,

$$I_a = 0.2S \tag{5}$$

Finally, the rainfall-runoff equation can be simplified in terms of only *P* and *S* by substituting 0.2S for I_a in eq. (3), and then becomes:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{6}$$

The resulting value, *Q*, represents the quantity of runoff that is accumulated from the storm event.

3.2.2.4 Step 4: Determine time of concentration (*Tc*) for the development site (pre-development conditions)

The time of concentration represents the travel time for runoff in the most remote part of each drainage area to reach the proposed GSI (Atlanta Regional Commission 2016). Typically, urban areas translate to shorter times of concentration because drainage areas are smaller and contain a high percentage of impervious surfaces. To calculate *Tc*, two types of flow must be accounted for. First, sheet flow, represented by eq. (7), is used to calculate the travel time of cross slope runoff, or runoff that drains from the center of the roadway to the gutter. For simplicity, sheet flow was assumed to occur in the same direction over the entire width of the roadway (Figure 3).

$$T_1 = \frac{0.42(nL)^{0.8}}{60(P_2)^{0.5}(S)^{0.4}} \tag{7}$$

where:
T_1 = travel time (hr)
n = manning roughness coefficient
L = flow length (ft)
S = land slope (ft/ft)
P_2 = 2-year, 24-hour rainfall (in) as calculated below

For concrete and asphalt roadways, n = 0.11 (Appendix B). Flow length (L) is the measured width of each roadway segment. P_2 is retrieved by multiplying the intensity (i) of a 2-year, 24-hour storm, by 24 hours:

$$P_2 = i\frac{in}{hr}x\ 24\ hrs$$

After runoff reaches the gutter, it is assumed that the type of flow changes from sheet flow to shallow concentrated flow, per Figure 3.

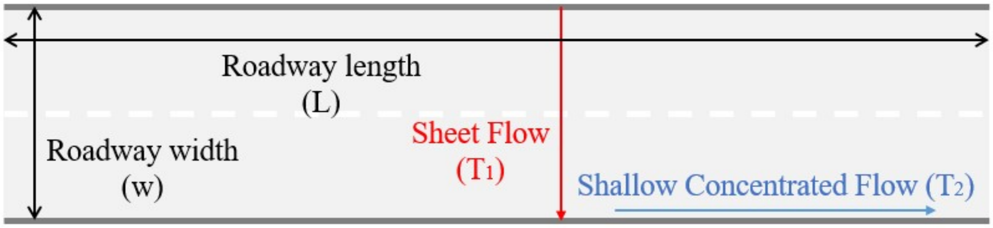


Figure 3 – Sheet flow versus shallow concentrated flow for travel time calculations

A separate equation is given to calculate Tc for shallow concentrated flow (Atlanta Regional Commission 2016):

$$T_2 = \frac{L}{3600V} \qquad (8)$$

where:
T_2 = travel time (hr)
L = flow length (ft), corresponding to the length of each segment
V = average velocity (ft/s) per eq. (9) below
60 = conversion factor from seconds to minutes

For paved areas, average velocity (V) can be calculated as follows:

$$V = 20.33(S)^{0.5} \qquad (9)$$

where:
V = average velocity (ft/s)
S = slope of hydraulic grade line (watercourse slope, ft/ft)

The total time of concentration for each segment is then calculated by adding the two travel times.

3.2.2.5 Step 5: Compute peak discharge (Q_p) for the pre-development condition

The pre-development peak discharge will ultimately determine the ratio of pre-development to post-development discharge, which is used to determine the required storage volume. To calculate the peak discharge, the following equation is used:

$$Q_P = q_U A Q F_p \tag{10}$$

where:
Q_p = peak discharge (cfs)
q_u = unit peak discharge (cfs/mi^2/in)
Q = runoff (in) per calculations in Step 3
A= area (mi^2)
F_p= pond and swamp adjustment factor

First, the unit peak discharge (q_u) is retrieved using Figures 4 and 5. Since this analysis focuses on the Atlanta region, Figure 5 represents a Type II rainfall distribution.

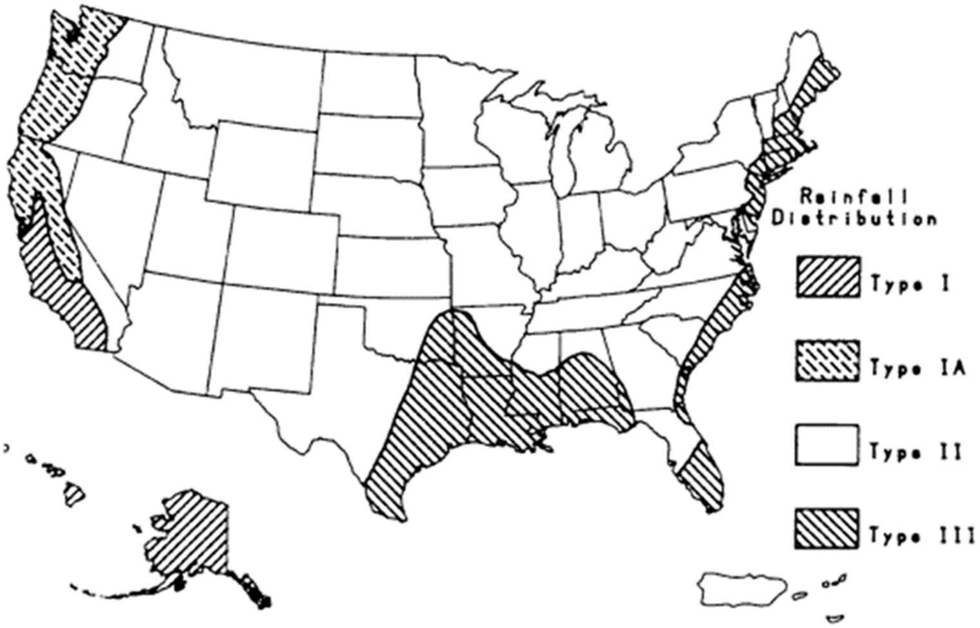


Figure 4 – Approximate geographic boundaries for NRCS TR-55 rainfall distribution

(GSMM Vol 2, 2016)

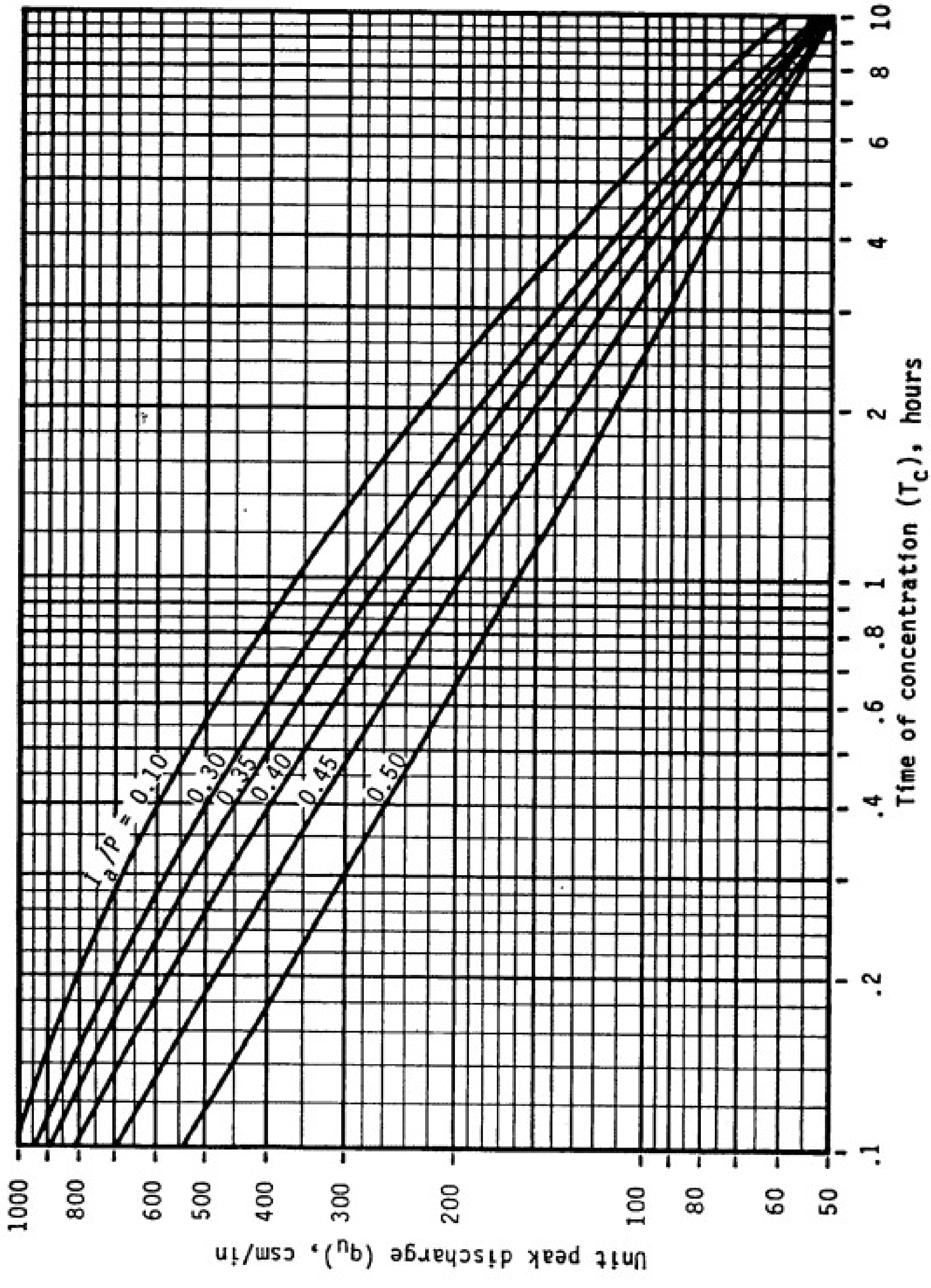


Figure 5 – NRCS TR-55 Type II unit peak discharge graph (GSMM Vol 2, 2016)

The Unit Peak Discharge Graph first requires the division of two known values: I_a and P. If $\frac{I_a}{P}$ does not align precisely with the values of the graph, the limiting line should be used. Area (A) is the segment area in square miles and runoff (Q) was calculated in Step 3. The pond adjustment factor (F_p) is retrieved from Table 2. Since the study area consists only of roadways and their immediate adjacent area, it is assumed $F_p = 1$. With each variable defined, the peak discharge (Q_P) can be calculated for each segment.

Table 2 – Pond and swamp adjustment factors *(GSMM Vol 2, 2016)*

Pond and Swamp Areas (%)*	F_p
0	1.00
0.2	0.97
1.0	0.87
3.0	0.75
5.0	0.72

*Percent of entire drainage basin

3.2.2.6 Step 6: Determine the ratio of peak outflow to peak inflow ($\frac{q_o}{q_i}$)

The ratio $\frac{q_o}{q_i}$ is needed to determine the storage volume for the 25-year, 24-hour storm. Given the peak unit discharge calculated in the previous step, and a known detention time (T), which in this case will be 24-hours, Figure 6 can be used to determine $\frac{q_o}{q_i}$.

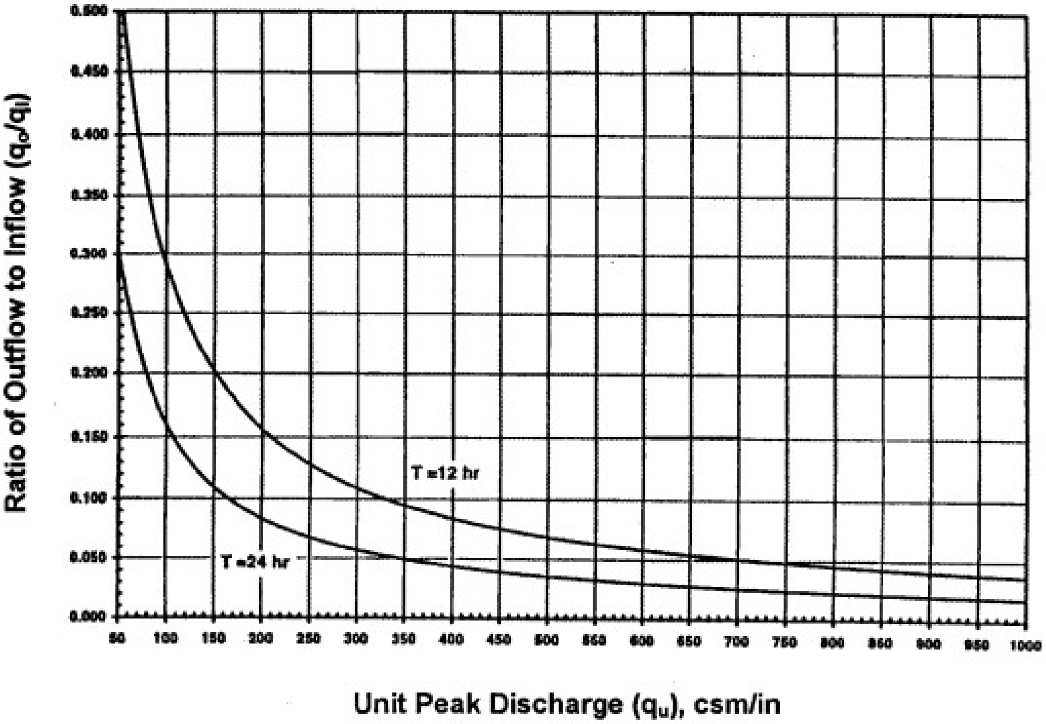


Figure 6 – Detention time vs. discharge ratios (GSMM Vol 2, 2016)

3.2.2.7 Step 7: Calculate the Ratio of Required Storage Volume to Stormwater Runoff Volume, $(\frac{V_S}{V_r})$

The ratio of required storage volume to stormwater runoff volume is given by eq. (11).

$$\frac{V_S}{V_r} = 0.672 - 1.43\left(\frac{q_o}{q_i}\right) + 1.64\left(\frac{q_o}{q_i}\right)^2 - 0.804\left(\frac{q_o}{q_i}\right)^3 \qquad (11)$$

where:
V_S = required storage volume (acre-feet)
V_r = runoff volume (acre-feet)
Q = runoff (in) per Step 3
$\frac{q_o}{q_i}$ = ratio of outflow to inflow per Step 6

3.2.2.8 Step 8: Determine the required storage volume, (V_s)

The final step requires calculation of the required storage volume (V_s) to be captured by GSI. V_s is calculated using the TR-55 equation for a Type II storm:

$$V_s = \frac{\frac{V_s}{V_r} Q_d A}{12} \qquad (12)$$

where:
$\frac{V_S}{V_r}$ = ratio of required storage volume to required runoff volume per Step 7
Q_d = pre-development runoff for the design storm (in) per calculations in Step 3
A = total drainage area (acres) which corresponds to the area of each segment.

3.2.3 100-Year, 24-Hour Storm Scenario

The last set of calculations compute the storage volume for runoff associated with a 100-year, 24-hour storm (1% chance of occurrence in any given year). Although the runoff volume for a storm of this magnitude will likely exceed the available capacity of GSI installed in the ROW, this scenario is presented to support the argument of solely relying on GSI to capture and treat stormwater during an intense storm event. Capturing the 100-year storm with GSI does not inherently mean total separation within the CSA, but it is a significant step to reducing combined sewer dependency and eliminating CSO events. Sources of stormwater runoff outside of the ROW, such as roof downspouts or private storm drains would need to be addressed before total separation is possible. However, roadways make up the overwhelming majority of impervious surfaces and are the primary source of runoff within an urban area (Frazer 2005). Moreover, they present one of the most perplexing issues in stormwater mitigation because there is limited space to store excess runoff within the ROW. Hence, this storm evaluates whether green streets can remove all drainage from the ROW without physically separating the infrastructure. Even if treated stormwater eventually enters the sewer (i.e., detention rather than retention), the rate at which runoff enters the system can be drastically reduced with GSI, which enables the sewers to function as intended through even the largest storms. After all roadway segments within the CSA are reconstructed, sewers are left to operate primarily for sanitary flows and secondarily for stormwater collection.

The results from this scenario will demonstrate the resources required to construct an off-line stormwater system that is capable of handling runoff in a major storm event. The process is nearly identical to the 25-year storm calculations, except a different rainfall intensity is retrieved in Step 1. Instead of the 25-year, 24-hour intensity, the 100-year, 24-hour intensity (i) is used. The remaining steps as outlined in the previous section are then carried out for the remainder of the 100-year, 24-hour storm calculations.

3.3 Green Stormwater Infrastructure

This section provides detailed information for each type of GSI that will be considered for green street projects within the scope area. Each segment will be evaluated to determine the most appropriate GSI solution(s) based on roadway type, storage needs, construction cost, maintenance burden, and anticipated co-benefits. Each type of GSI is accompanied by a standard detail to calculate available storage volume and construction cost. Since the main case study in this analysis focuses on the Atlanta region, all standard details have been retrieved from the City of Atlanta Guide for Green Infrastructure Stormwater Management Practices for Small Commercial Development. For regions outside of the southeastern US, elements such as vegetation type or soil depth may need to be modified. Maintenance practices may also be more intensive in colder climates where GSI requires winterization.

Green street projects are likely to encounter a wide array of site-specific challenges, so flexibility within standard details and specifications is paramount. For example, Portland's Green Street Notebook contains several details for each type of GSI based off lessons learned from past projects (City of Portland 2007). Consistent, yet flexible standards promote cost savings because they streamline the construction process and anticipate common site issues. Continuity in green street design projects also enables an accurate forecast of the frequency and type of maintenance required to keep GSI functioning properly and assists the governing municipality in determining proper schedules and cost profiles for routine operations and maintenance activities (Cammarata 2014).

The standard details will determine a planning level cost estimate for each type of GSI given their materials and design assumptions listed in Appendix A. A relative maintenance burden (high, medium, or low) is also assigned to each type of GSI based on information from BMP checklists provided by the 2001 Georgia Stormwater Management Manual (Atlanta Regional Commission 2001). Some roadway segments will have multiple solutions that could be appropriate, but construction cost and maintenance burden will largely determine the ideal solution. In addition to construction cost and maintenance burden, the ideal solution considers factors such as projected co-benefits and local GSI preference. Section 3.4.2 provides a detailed descriptions of GSI criteria included in this analysis. The following subsections describe each type of GSI in detail.

3.3.1 Bioretention

Bioretention basins, also commonly referred to as rain gardens, consist of a combination of vegetation, mulch, and engineered soil (Figure 7) to capture and treat stormwater runoff (Davis et al. 2009). Bioretention areas are typically shallow (less than four feet), but vary widely in shape and placement, making them a suitable option for a large range of applications (US EPA 2021) . In the case of green streets, bioretention basins are typically installed in medians or shoulders, as shown in Figure 8. For high-traffic areas, basins may be enclosed within a curb. During a storm event, runoff is directed to the basin via an opening in the curb, or curb cut, to guide flow into the bioretention area where it is treated through infiltration. If no curb exists, drainage is accepted into the basin via sheet flow.

Ideally, runoff collected in a bioretention basin will be captured completely through infiltration and retention, but a basin may also serve as a detention system by slowly releasing runoff into the nearby storm sewer via underlying drainage structures. Urban areas typically have polluted or poorly draining soils, which can be replaced with engineered fill to promote higher rates of infiltration. This analysis assumes a constant infiltration rate for all sites across the CSA per City of Atlanta stormwater guidelines (City of Atlanta DWM 2014). However, soil testing should be performed onsite to verify the infiltration rate prior to design and construction. This analysis also assumes that an overflow structure with an outlet to the underlying sewer is provided to prevent flooding during extreme storm events and reduce instances of long-term ponding at the basin's surface (Roy-Poirier, Champagne, and Filion 2010). The standard detail in Appendix A will serve as the typical bioretention basin proposed in all applications for the remainder of this analysis.

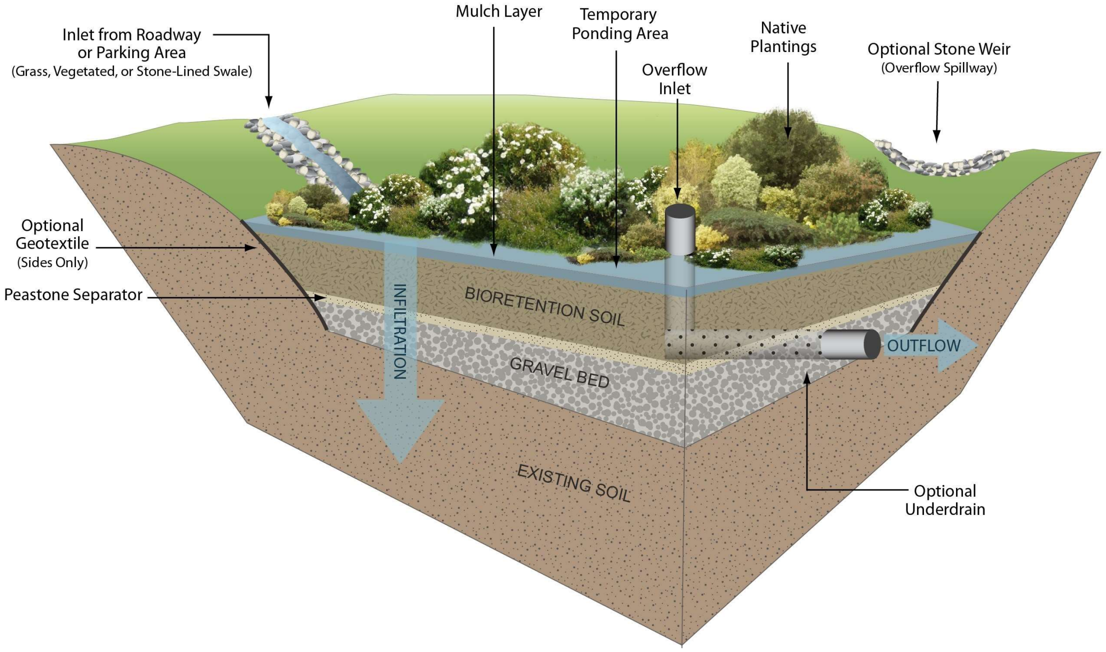


Figure 7 – Typical diagram of a bioretention area and its components
(Massachusetts Department of Environmental Protection, 2021)

Figure 8 – Bioretention placement between curb and sidewalk
(Ecological Landscape Alliance, 2019)

Bioretention areas offer several advantages in the design of green streets. A careful selection of mulch, soil, and plantings can efficiently remove pollutants commonly found in roadway drainage, including heavy metals, oil, and grease (Prince George's County 2007). Bioretention vegetation also provides co-benefits such as improvement to site aesthetics, reduction of noise, and pedestrian protection from sun and wind (Roy-Poirier, Champagne, and Filion 2010). Commonly cited issues with bioretention areas include conflict with underlying utilities and increased maintenance due to abundant vegetation (Prince George's County 2007). Furthermore, bioretention basins require placement in relatively flat areas (US EPA 2021). Seattle has been able to incorporate steep slopes into their designs, however, by making use of a cascading bioretention design that gradually steps down over the length of a city block (Seattle Public Utilities 2022).

3.3.2 Bioswale

Bioswales, also commonly referred to as vegetated or enhanced swales, are longitudinal bioretention areas used for conveyance and retention of runoff (NACTO 2013). Bioswales are shallow depressions, usually parabolic or trapezoidal, that utilize vegetation and soil to promote infiltration (US EPA 2021). Bioswales are ideal for roadway shoulders or rights-of-way that have continuous stretches of land (US EPA 2021). They collect and convey water and can easily be used in conjunction with, or as a pretreatment mechanism to, other GSI solutions. In the case of a high water table, bioswales are designed as “wet” swales, meaning ponding is continuously present (Minnesota Pollution Control Agency 2018b). Alternatively, a dry swale only contains ponding after a storm event and runoff is ultimately infiltrated or conveyed downstream (i.e. storm sewer or other GSI) over time (Minnesota Pollution Control Agency 2018b). For poorly draining soils, dry swales contain underdrains to prevent standing water and promote increased rates of infiltration.

Bioswales are a viable option for green streets with limited ROW space. They also serve as a low-cost alternative for traditional curb and gutter systems on low volume streets. While the layout of a bioswale is relatively flexible, it will function best along long, uninterrupted stretches of land, which may be a challenge for sites in urban setting. Because bioswales are small and shallow, they may not serve as a stand-alone solution to eliminating local flooding caused by excessive runoff (NACTO 2013). Ideally, they should be paired with another type of GSI where infiltration is the primary hydrological function. Figure 9 shows a roadside application of a bioswale within the ROW. Appendix A contains a standard detail that will be used for all proposed applications in later sections of this paper.

Figure 9 – Bioswale placement between roadway and sidewalk
(Mark M. Holeman Inc, 2014)

3.3.3 Stormwater Planter and Curb Extension

Stormwater planters and curb extensions are similar to bioretention areas in that they consist of a shallow excavation that contains engineered soils, mulch and vegetation (Charles River Watershed Association 2008). They are typically designed to capture and treat runoff from smaller drainage areas and are commonly enclosed within a curb, making them a popular choice for urban settings (Figure 10) (US EPA 2021). During a storm event, runoff is directed through a drainage structure, or curb cut, and into the planter area where it slowly infiltrates through vegetation and soil media. Although the goal is to achieve complete infiltration, underdrains are typically installed to promote drainage after a large storm event and reduce prolonged ponding. Stormwater planters may also utilize an impermeable liner to protect adjacent structures or, in the case of heavily polluted runoff, prevent groundwater contamination (US EPA 2021). Further site analysis must be performed to determine whether an impermeable liner is necessary. In this analysis, it is assumed that permeable liners are not required.

Figure 10 – A stormwater planter with a decorative railing in an urban setting
(Mississippi Watershed Management Organization, 2021)

Stormwater planters are generally installed in the landscape buffer zone, adjacent to the existing roadway. They may also be placed at the back of sidewalk depending on site conditions. Curb extensions are installed within the existing roadway footprint, usually at an intersection or mid-block. Figure 11 shows several locations that are commonly considered for stormwater planters or curb extensions in relation to the roadway.

Figure 11 – Stormwater planter and curb extension placements
(National Association of City Transportation Officials, 2021)

Stormwater planters and curb extensions are widely applicable in urban settings and offer aesthetic enhancements to the streetscape through the addition of vegetation (Charles River Watershed Association 2008). Curb extensions also serve as traffic calming mechanisms by visually reducing the number of travel lanes, which decreases vehicular speed (City of Philadelphia 2016) . When installed at crosswalks, curb extensions improve pedestrian safety by increasing a driver's ability to see pedestrians entering the travel-way

(NACTO 2017c). High construction cost is the most commonly cited drawback to stormwater planters and curb extensions versus other types of GSI (Cahill, Godwin, and Tilt 2018). Increased costs typically stem from structural curb installation, which is required in high-traffic urban areas. Maintenance costs vary widely depending on vegetation and mulch selection (Cahill, Godwin, and Tilt 2018). Careful consideration of site-specific environmental factors and the use of plants native to the region reduce maintenance frequency and cost (City of Boise 2000). Local and state stormwater agencies typically publish recommended plant lists that are available online.

3.3.4 Infiltration Trench

Infiltration trenches are linear areas that have been excavated, backfilled with sand and stone, and covered with large aggregate or grass (US EPA 2021). Replacing urban or native soils with coarse aggregate increases the amount of void space available underground for runoff storage and allows more time for runoff to infiltrate into deeper soil (Minnesota Pollution Control Agency 2020). Infiltration trenches should be at least two feet wide, while the depth can vary from three feet to twelve feet (Minnesota Pollution Control Agency 2018a). A deeper trench allows more storage, but underlying utilities can limit depth in urban areas. Additional components of infiltration trenches include geotextile liners that prevent migration of aggregate and observation wells that allow for routine inspection and monitoring of water levels (Virginia Tech 2013). Infiltration trenches function best when they are coupled with pre-treatment mechanisms, such as bioswales or grass buffers. When designed properly, pre-treatment devices filter large debris to prevent it from entry into the trench and obstruction of void space within the aggregate (Virginia Tech 2013).

Infiltration trenches are an ideal roadside application because of their linear shape and ability to store large runoff volumes (Virginia Tech 2013). Although infiltration trenches do not provide the same aesthetic benefits as the aforementioned types of GSI, they have a distinct advantage in placement because they can be installed under any element in the ROW, as long as runoff can penetrate the surface. Figure 12 provides an example of an infiltration trench placement in relation to paved surfaces.

Figure 12 – Infiltration trench placement at back of sidewalk
(Landscape Architecture Foundation, 2021)

3.3.5 Subsurface Infiltration and Detention

Subsurface infiltration and detention systems are a relatively new subset of GSI that have gained traction in recent years. Most subsurface systems contain some type of proprietary chamber made of strong plastic or concrete to maximize void space underground and increase the amount of available runoff storage (US EPA 2021). Large aggregate is placed above, below, and between the chambers for strength and additional storage, then a surface treatment is installed overtop, which can include pavement, landscaping, or grass (US EPA 2021). Systems may be lined with an impermeable liner when placed over highly polluted soil and they typically have an overflow structure that outlets into the sewer system (Philadelphia Water Department 2019) . A higher volume of runoff usually favors detention over retention because infiltration alone cannot adequately drain the entire system in the days following a large storm. Ideally, runoff isn't released into the sewer, and is instead treated onsite and harvested for other uses, such as irrigation for landscaping (US EPA 2021).

Since most systems are proprietary and research is limited, public entities tend to shy away from the use of subsurface infiltration and detention systems (Atlanta Regional Commission 2016). Furthermore, large subsurface systems are not always appropriate in urban settings because they require physical clearance from other underground utilities and building foundations (Philadelphia Water Department 2019). However, when surface space is limited, these systems can capture large volumes underground while the area aboveground can be paved or landscaped (Philadelphia Water Department 2019). Construction cost and maintenance burden data is not widely available, but many manufacturers tout quick installation due to the use of pre-cast units (ECT Team 2007).

Since subsurface systems do not contain vegetation, they tend to have a relatively low maintenance burden. Routine monitoring through inspection ports is recommended to ensure the system is functioning properly (Philadelphia Water Department 2019).

To maintain the maximum feasibility for a public entity within this research, the application of subsurface infiltration and detention practices is only proposed as a last resort. Only once when every other GSI option has been deemed inadequate at storing the runoff volume necessitated by a given storm event are subsurface infiltration and detention systems recommended. Figure 13 illustrates the general components of a subsurface infiltration system while standard details of a proprietary system are provided in Appendix A.

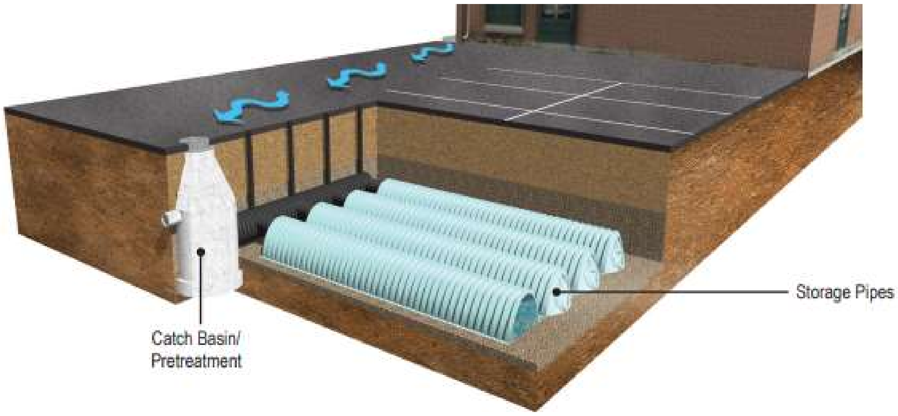


Figure 13 – A subsurface infiltration and detention system that utilizes plastic chambers for runoff storage
(City of Detroit, 2021)

3.3.6 Permeable Pavement

Permeable pavement refers to asphalt, concrete, or interlocking paver systems that contain a high number of voids to maximize infiltration of surface runoff (US EPA 2021). Pervious asphalt and concrete both utilize large aggregate within their pavement mix to allow rapid infiltration of surface runoff which is then stored in an underlying stone reservoir (Virginia Tech 2013). Permeable pavers also utilize a stone reservoir, but runoff enters through the space between each paver rather than permeating through the pavement's surface (US EPA 2021). Regardless of the surface material, permeable pavements function best when coupled with pre-treatment, such as grass swales or gravel beds, that filter large debris and prevents voids from clogging to support infiltration and promote long-term performance (Minnesota Pollution Control Agency 2017).

Pavers typically require more capital upfront and are less costly to maintain in the long term, while concrete and asphalt are less expensive to construct, but more expensive to maintain. The material cost of pavers is much higher than that of concrete or asphalt, but as pavers need to be replaced, they can be switched out individually or in small sections (US EPA 2021). The process of repairing concrete or asphalt is typically performed on a larger scale because it must be produced in large batches to ensure quality control and maintain the structural integrity of the roadway (US EPA 2021).

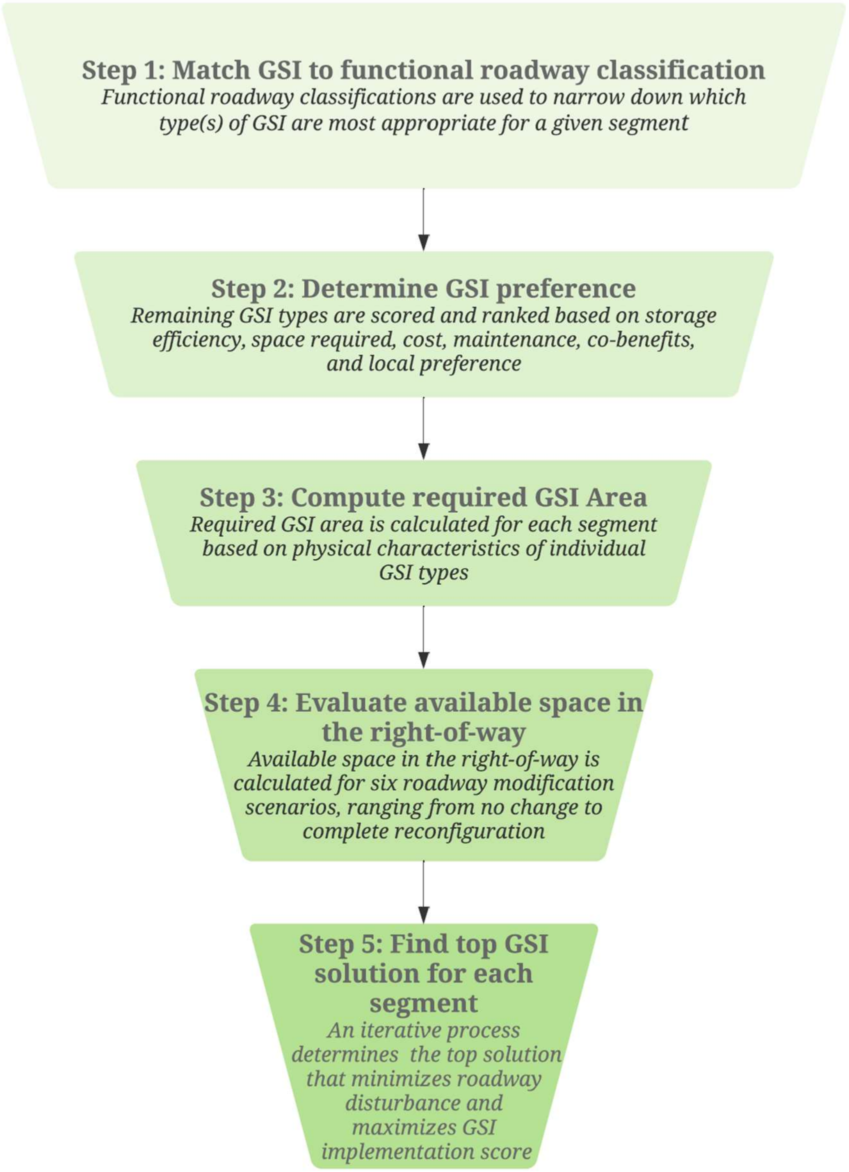
Once installed, permeable pavement appears and functions like conventional pavement, providing both advantages and disadvantages. First, every type of GSI presented thus far has required that space in the ROW be reallocated from its current use. Permeable pavement, however, does not require additional space, allowing both the roadway and sidewalk to retain their existing functionality, all while capturing runoff. Permeable pavement is similar to its conventional counterparts, which can cause specialized construction or maintenance methods to be overlooked. For example, construction of conventional pavement requires compaction within the subbase and base of the pavement section to increase the strength of the roadway, while permeable pavements require tilled, uncompacted subbase and base layers to provide void space and ensure higher rates of infiltration (Hein and Schaus 2013). Furthermore, permeable pavement must be routinely vacuumed or pressure washed to ensure void space is clear of debris (Kevern 2011). If contractors and maintenance personnel are unaware of these subtle, yet important differences, permeable pavement will function like conventional pavement and GSI benefits will be unrealized.

Although permeable pavement systems may appear to be the most appropriate solution for retrofitting conventional roadways into green streets, their application is somewhat limited due to their decreased load-bearing capacity – a product of increased void space (Virginia Tech 2013). Within the ROW, permeable pavements are most appropriate for roadways with lower traffic volumes, or for parking lanes, gutters, and sidewalks (Minnesota Pollution Control Agency 2017). In this analysis, the placement of permeable pavement is limited to parking lanes to provide adequate real estate for other utilities in the ROW and reduce loading from moving vehicles. Figure 14 shows permeable pavement placed in the parking lane between a conventional asphalt roadway and a concrete curb and gutter. Refer to Appendix A for all permeable pavement standard details.

Figure 14 – Interlocking permeable pavers in the parking lane
(National Association of City Transportation Officials, 2021)

3.4 Green Street Toolkit

This section discusses the process to determine which type of GSI is most appropriate for a given roadway segment. The information presented in this section is intended to build upon the existing conditions assessment and GSI descriptions outlined in the previous section. The flowchart on the next page (Figure 15) provides an overview of the Toolkit process and the following subsections provide detailed descriptions for each step.



Step 1: Match GSI to functional roadway classification
Functional roadway classifications are used to narrow down which type(s) of GSI are most appropriate for a given segment

Step 2: Determine GSI preference
Remaining GSI types are scored and ranked based on storage efficiency, space required, cost, maintenance, co-benefits, and local preference

Step 3: Compute required GSI Area
Required GSI area is calculated for each segment based on physical characteristics of individual GSI types

Step 4: Evaluate available space in the right-of-way
Available space in the right-of-way is calculated for six roadway modification scenarios, ranging from no change to complete reconfiguration

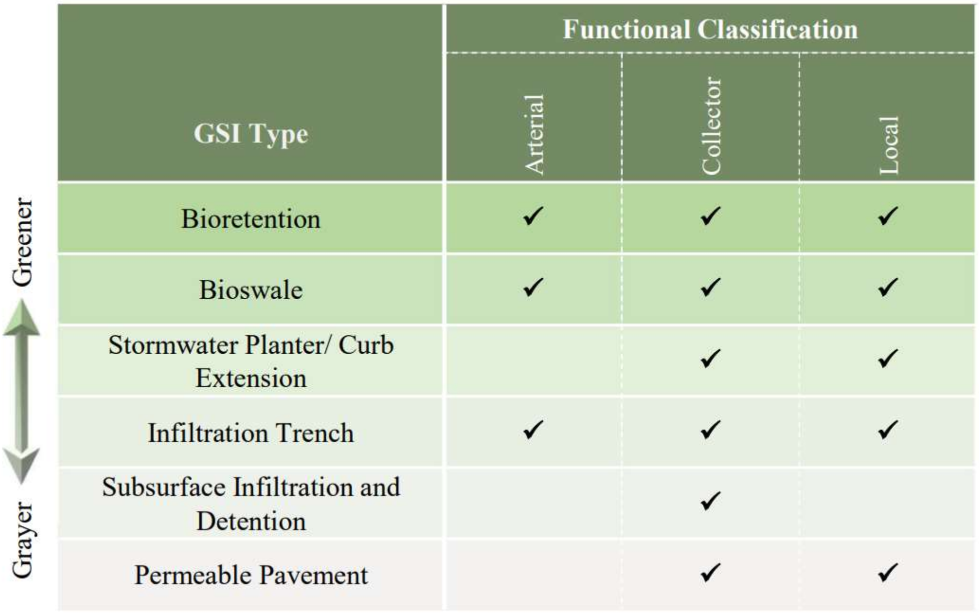
Step 5: Find top GSI solution for each segment
An iterative process determines the top solution that minimizes roadway disturbance and maximizes GSI implementation score

Figure 15 – Green Street Toolkit process overview

3.4.1 *Step 1: Match GSI to Appropriate Functional Classification*

In the first step, functional roadway classifications defined by FHWA are used to determine which types of GSI are most appropriate for a given segment, per the EPA Green Streets Handbook (US EPA 2021). Table 3 provides a list of functional classifications and appropriate types of GSI to be used within each classification. For example, an arterial segment should utilize bioretention, bioswales, or infiltration trenches only, and no further types of GSI should be considered.

Table 3 – Appropriate GSI types per functional roadway classification
(US EPA 2021)



GSI Type	Functional Classification		
	Arterial	Collector	Local
Bioretention	✓	✓	✓
Bioswale	✓	✓	✓
Stormwater Planter/ Curb Extension		✓	✓
Infiltration Trench	✓	✓	✓
Subsurface Infiltration and Detention		✓	
Permeable Pavement		✓	✓

3.4.2 Step 2: Determine GSI Preference

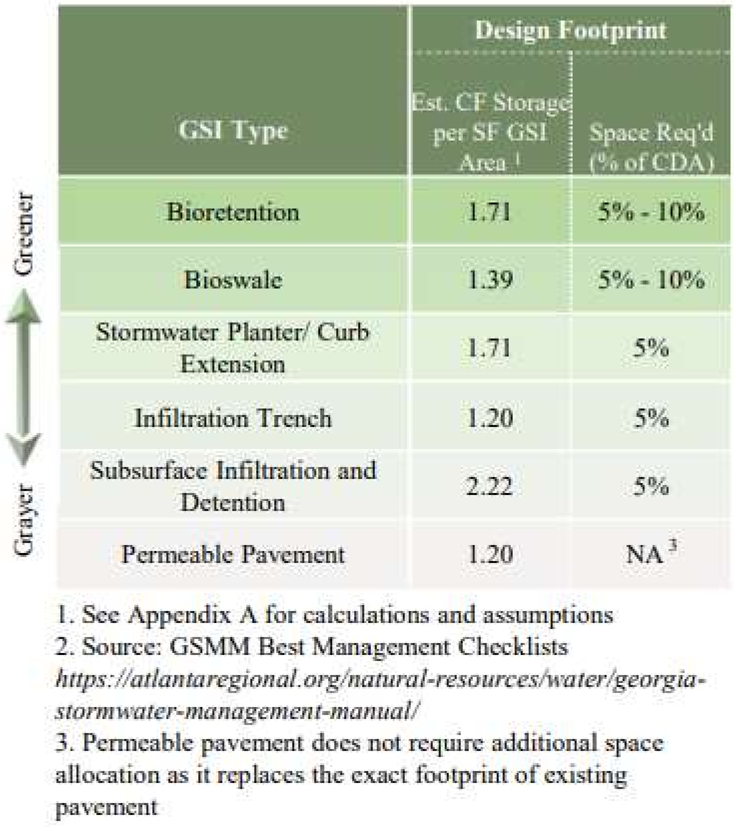
Once appropriate types of GSI are identified, overall preference is determined via the following criteria: GSI storage, space required for installation, construction cost, relative maintenance burden, and projected co-benefits. The end of this section presents a rational scoring system that uses the abovementioned criteria to rank GSI selection and implementation.

3.4.2.1 Step 2a: GSI Storage Capacity and Footprint

The estimated storage for each type of GSI is calculated using design assumptions gathered from each standard detail. A list of design assumptions is provided for each type of GSI in Appendix A. The main factors that influence GSI storage are media type, media depth, and ponding depth. Media type refers to a combination of soil, aggregate, or engineered fill, all of which have a specific void ratio. The void ratio determines how much space exists within the media for runoff to be stored. Media depth refers to the depth that media (i.e., soil or aggregate) is placed below grade. Since utility and structural conflicts are likely in urban scenarios, media depths are assumed to be relatively shallow, ranging from three to five feet, depending on GSI type. Ponding depth refers to the depth of runoff stored above the planting media at the GSI’s surface. The overall storage volume is intended to be a realistic estimation that accounts for urban conditions rather than a true maximum allowable storage volume. Further analysis regarding underlying utilities will determine the ultimate depth of the GSI, which will directly affect the estimated storage volume.

The space required for each type of GSI as a percentage of contributing drainage area (CDA), which in this case is equal to the area of each segment, is another important consideration. Required space is a crucial consideration in urban conditions when ROW space is limited and the other components, such as roadways or sidewalks, are competing for real estate along a segment. Table 4 provides an estimate for cubic feet (CF) of storage per square foot (SF) of GSI surface area, and the space required as a percentage of the CDA.

Table 4 – GSI storage and contributing area



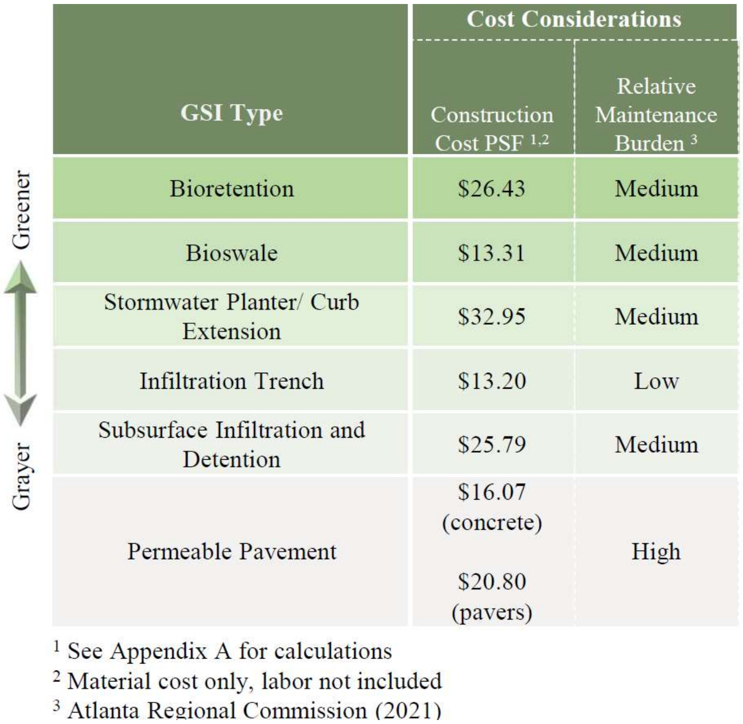
GSI Type	Design Footprint	
	Est. CF Storage per SF GSI Area [1]	Space Req'd (% of CDA)
Bioretention	1.71	5% - 10%
Bioswale	1.39	5% - 10%
Stormwater Planter/ Curb Extension	1.71	5%
Infiltration Trench	1.20	5%
Subsurface Infiltration and Detention	2.22	5%
Permeable Pavement	1.20	NA [3]

1. See Appendix A for calculations and assumptions
2. Source: GSMM Best Management Checklists *https://atlantaregional.org/natural-resources/water/georgia-stormwater-management-manual/*
3. Permeable pavement does not require additional space allocation as it replaces the exact footprint of existing pavement

3.4.2.2 Step 2b: Construction Costs and Maintenance Burden

Next, the construction cost per square foot is calculated for each type of GSI in accordance with the standard detail and design assumptions outlined in Appendix A. Due to high variation in wages, construction costs only include raw material. Appendix A provides a list of components and cost calculations for each type of GSI in 2021 dollars. Final costs are expected to vary due to existing site conditions and external economic factors. Recurring operational and maintenance costs will vary more than construction costs due to final plant selection, location within the ROW, and other site-specific conditions. Therefore, a relative maintenance burden is assigned to each type of GSI rather than a hard cost. Table 5 provides a summary of costs per SF of GSI area and relative maintenance burdens for each type of GSI. Stormwater planters and curb extensions have the highest cost due to curb installation, followed by bioretention and subsurface infiltration. Permeable pavement has a moderate construction cost, but a relatively high maintenance burden. Bioswales and infiltration trenches tend to use less variety in materials, which contributes to their low capital cost.

Table 5 – GSI construction cost PSF and relative maintenance burden



GSI Type	Cost Considerations	
	Construction Cost PSF [1,2]	Relative Maintenance Burden [3]
Bioretention	$26.43	Medium
Bioswale	$13.31	Medium
Stormwater Planter/ Curb Extension	$32.95	Medium
Infiltration Trench	$13.20	Low
Subsurface Infiltration and Detention	$25.79	Medium
Permeable Pavement	$16.07 (concrete) $20.80 (pavers)	High

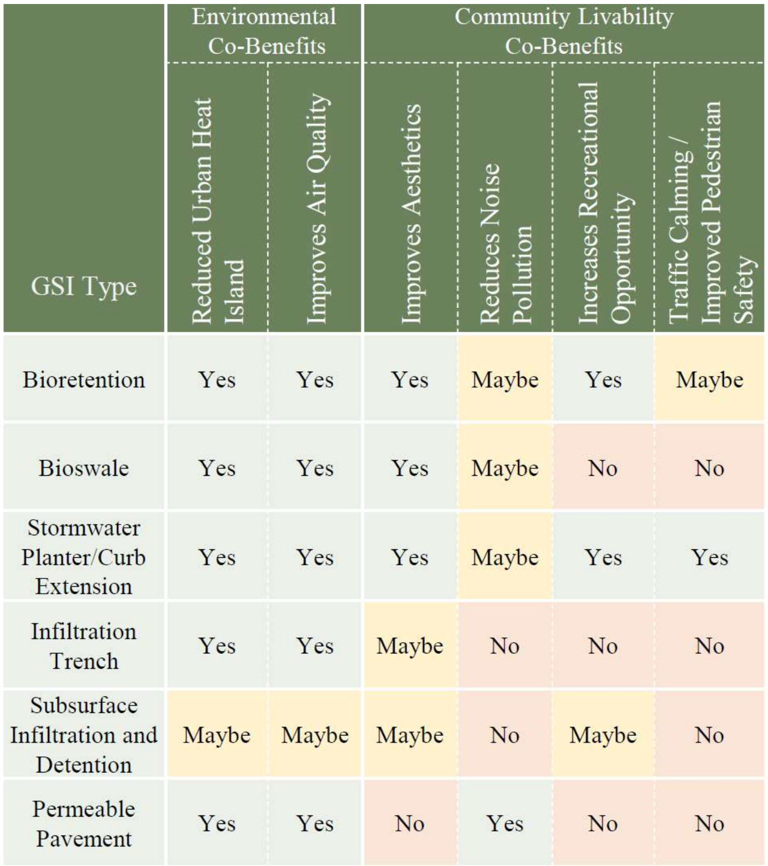
[1] See Appendix A for calculations
[2] Material cost only, labor not included
[3] Atlanta Regional Commission (2021)

3.4.2.3 Step 2c: Co-benefits

Estimated GSI storage, required space, construction cost, and relative maintenance burden are the primary drivers for which type of GSI should be installed along each segment, but co-benefits, or benefits that are indirectly realized once a specific type of GSI is installed, are also an important because they offer supplementary environmental and social benefits. Table 6 lists co-benefits for each type of GSI, although the list is not exhaustive. In addition to those listed, all GSI proposed in this research will reduce water treatment needs, local flooding, and an area's dependency on gray infrastructure.

Table 6 – GSI co-benefits

(Adapted From Center For Neighborhood Technology 2010)



GSI Type	Environmental Co-Benefits		Community Livability Co-Benefits			
	Reduced Urban Heat Island	Improves Air Quality	Improves Aesthetics	Reduces Noise Pollution	Increases Recreational Opportunity	Traffic Calming / Improved Pedestrian Safety
Bioretention	Yes	Yes	Yes	Maybe	Yes	Maybe
Bioswale	Yes	Yes	Yes	Maybe	No	No
Stormwater Planter/Curb Extension	Yes	Yes	Yes	Maybe	Yes	Yes
Infiltration Trench	Yes	Yes	Maybe	No	No	No
Subsurface Infiltration and Detention	Maybe	Maybe	Maybe	No	Maybe	No
Permeable Pavement	Yes	Yes	No	Yes	No	No

3.4.2.4 Step 2d: GSI Implementation Score

The previous steps provide each factor required to determine which type of GSI is best suited for the roadway, including estimated storage, required space, construction cost, maintenance burden, and co-benefits. To determine which type of GSI is best, a weighted rating system is used. This step provides one example of how to rank GSI, but if a municipality were to establish a green streets program, weights of each criterion may shift depending on the goals the municipality wishes to achieve. In this case, storage capacity and required GSI area assume the greatest weight of to promote maximum physical feasibility, while construction cost and maintenance burden receive moderate weights to emphasize financial and operational feasibility. Co-benefits and local preference have the lowest weights because they are not the main objectives of the green streets program proposed in this research. Some green streets programs may prioritize co-benefits over feasibility and some programs may have multiple weighting systems depending on neighborhood type or functional classification. Table 7 provides a summary of ranking structure and an explanation for how each value was assigned.

Table 7 – GSI scoring criteria and ranking structure

Criteria	Summary and Ranking Structure
Storage	GSI is ranked from lowest storage PSF to highest storage PSF. A 1 represents the lowest storage and a 4 represents the highest. Some GSI types have the same storage, so some rankings (e.g. bioretention and stormwater planter) have the same value.
Space Required	The space required for each type of GSI is measured as a percentage of contributing drainage area that must be utilized strictly for GSI. GSI types are ranked against each other and ordered from most space required (score of 1) to least space required (score of 3)
Construction Costs	The six types of GSI are ranked in order of construction costs. A 1 represents the highest cost and a 6 represents the lowest cost.
Maintenance Burden	Relative maintenance burden is ranked from 1-3. A 1 represents a high maintenance burden compared to all types of GSI, a 2 represents a medium maintenance burden, and a 3 represents a low maintenance burden.
Co-benefits	All co-benefits listed in Table 5 are given the same weight. Each co-benefit has a value of 1. The score represents the total number of co-benefits a type of GSI has.
Local Preference	The City of Atlanta has their own ranking of preferred GSI types per the Green Infrastructure Stormwater Management Practices for Small Commercial Development Guide. A 6 represents the most preferred solution, while a 1 represents the least preferred. Although this example is specific to the City of Atlanta, it is important that any municipality determine either their local preference or evaluate the weight of co-benefits to fine tune the analysis to the specific needs and goals of the community.

After each type of GSI is ranked (per Table 7), the GSI types are given weighted implementation scores in Table 8. Table 8 reveals that bioretention and bioswales are most preferable, followed by permeable pavement, infiltration trench, subsurface infiltration and detention, and stormwater planters. The GSI scores calculated in Table 8 will be used in the next section to propose the top solution for each segment.

Table 8 – GSI implementation scores

	Criteria						
Weighting	3	3	2	2	1	1	
GSI Type	**Storage**	**Space Req'd**	**Constr. Cost**	**Maint. Burden**	**Co-benefits**	**Local Pref.**	**Total**
Bioretention	9	6	4	4	4	6	**33**
Bioswale	6	6	10	4	3	4	**33**
Stormwater Planter/ Curb Extension	9	3	2	4	5	2	**25**
Infiltration Trench	3	3	12	6	2	3	**29**
Subsurface Infiltration and Detention	12	3	6	4	0	1	**26**
Permeable Pavement	3	9	8	2	3	5	**30**

The scoring in Table 8 provides a consistent decision-making tool for local implementation of GSI and is intended to be used as a template for final GSI selection.

There are a variety of factors that could impact final GSI selection, and this scoring system prioritizes a GSI type's ability to provide an effective use of space that maximizes storage capacity. However, if there is abundant space in the ROW, a GSI type that prioritizes aesthetics may be preferred based on co-benefits. Stormwater planters rank poorly in this analysis due to high construction costs related to curb installation, but oftentimes a curb is necessary to manage traffic operations along a green street segment (Cahill, Godwin, and Tilt 2018).

Engineering guidance and community input during the planning and conceptual phases of a project is crucial for creating a green street that is functional for users of the roadway and fits within the context of the neighbourhood. It is equally important for decision-makers to stay flexible as the due diligence and design stages progress. In addition to GSI implementation score, site-specific existing conditions should guide the final decision and address the needs of all stakeholders.

3.4.3 Step 3: Compute Required GSI Area

Next, the treatment area required for each GSI type is calculated to determine how much ROW space is needed. Given the total runoff produced by each design storm (Section 3.2) and the estimated storage per type of GSI (Section 3.4.2.1), the required area for each GSI type proposed on given segment for a specified design storm can be calculated using eq. (13).

$$GSI\ Area\ Required_{segment\ i, GSI\ type\ j}(SF) = \tag{13}$$

$$\frac{Total\ Runoff\ Volume_{segment\ i,design\ storm\ j}(CF)}{Estimated\ GSI\ Storage_{GSI\ type\ j}\ (\frac{CF}{SF})}$$

If desired, the resulting metric can be broken down further to a linear foot basis by dividing the GSI area required by the total segment length:

$$GSI\ Area\ Required_{segment\ i,GSI\ type\ j}\left(\frac{SF}{LF}\right) = \frac{GSI\ Area\ Required_{segment\ i,GSI\ type\ j}(SF)}{Total\ Length_{segment\ i}\ (FT)} \qquad (14)$$

Breaking the GSI area required into a foot-by-foot basis provides a clearer calculation of the space required in the ROW for a specific location. This metric will be used for comparison to the calculations in Step 4, which derive the available ROW space per linear foot of each segment.

3.4.4 Step 4: Evaluate Available Space for GSI in the Right-of-Way

In prior steps, proposed GSI options for each segment were selected by functional classification, then ranked through an assessment of storage capacity, construction cost, and other factors. The last piece of information needed to calculate the top GSI solution for each segment is available space in the ROW. Ideally, the preferred GSI would be installed without major changes to the existing ROW section to minimize land disturbance and interference with traffic operations. However, modifications to the existing ROW may be essential for capturing runoff from larger storms because a more space for GSI will be required.

Available space within the ROW is calculated for each segment using six modification scenarios, each of which represents a range of reconstruction options. The best solution is Scenario 1, which presents minimal disruption to the ROW section and maintains the number of drive lanes, the presence of parking lanes, and the adherence to minimum sidewalk width per zoning standards. As the scenarios progress from one to six, more space is made available for GSI by reducing parking lanes and sidewalk width. Thus, Scenario 1 is the least-intensive modification scenario because it does not require any major reconstruction efforts. Scenarios 2-5 require a moderate amount of reconstruction to remove parking lanes and reduce sidewalk widths. Lasty, Scenario 6, a complete reconfiguration, requires significant changes to the roadway section that likely impact traffic operations. Table 9 provides a summary of modifications for each scenario.

Table 9 – Modification scenarios for roadway sections

↑ Less ROW Space Available

Preference / Scenario	Average Lane Width	Change in # of Drive Lanes	Change in # of Parking Lanes	Change in Sidewalk Width
1	No Change			
2	10 ft	No Change	-1	No Change
3	10 ft	No Change	-1	80% of Minimum Width, Not Less than 5'
4	10 ft	No Change	-2	No Change
5	10 ft	No Change	-2	80% of Minimum Width, Not Less than 5'
6	Major Reconfiguration / Varies - Further Engineering Analysis Needed			

↓ More ROW Space Available

In all scenarios, drive lanes are reduced to a width of ten feet, and in all but the last scenario, the number of drive lanes is maintained. The rankings prioritize pedestrian accommodation, so reducing the sidewalk width is only considered after at least one parking lane has been removed from the roadway section. In all cases, the sidewalk width is not reduced to less than five feet, in accordance with pedestrian standards set forth by the Americans with Disabilities Act (U.S. Department of Transportation Federal Highway Administration 2001).

While more ROW space is made available as scenarios progress, there are two exceptions. First, for roadways that do not have parking lanes, ROW width remains constant for Scenarios 1 and 2, then again for Scenarios 3 and 5, because the only retrofit opportunity applicable is a reduction of sidewalk width. Similarly, roadways with only one parking lane will have the same space available in Scenarios 2 and 4, as well as 3 and 5. Lastly, since the placement of permeable pavement is limited to parking lanes, the space available for GSI decreases as parking lanes are reduced.

The six roadway modification scenarios are applied to each roadway segment to determine the ROW width available for proposed GSI. For example, if Scenario 1 results in 5.0’ of available ROW width for GSI, then there are 5.0’W x 1.0 L = 5.0 SF available within each linear foot of that segment. Figure 16 provides a visual to accompany these calculations.

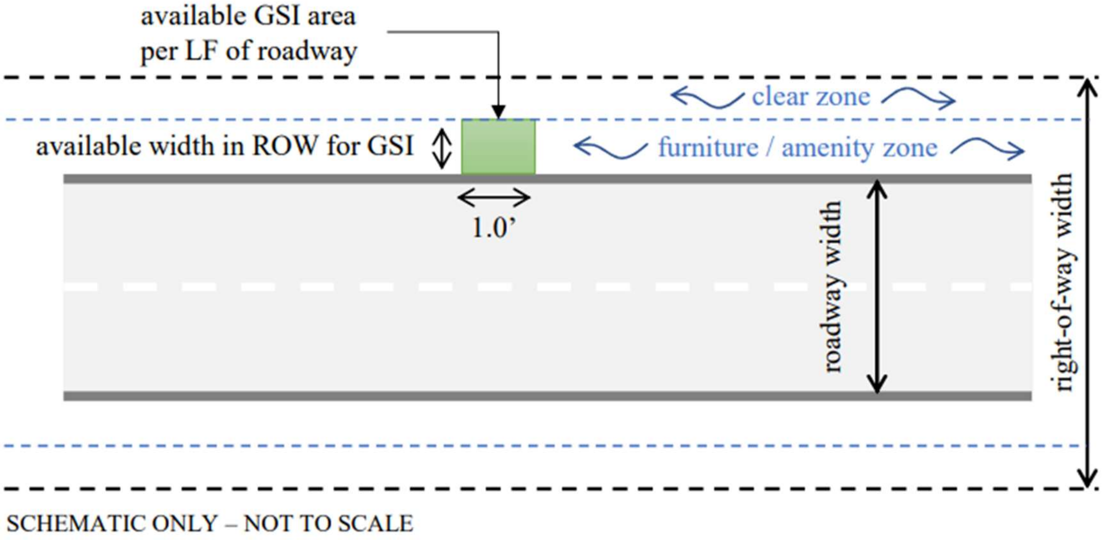


Figure 16 – Available GSI area[1]

Since this analysis is performed specifically for planning purposes, continuity between adjacent ROW sections is not considered. However, during the design phase of a project, care must be taken to ensure to align sidewalk and roadway locations in adjacent segments.

3.4.5 Step 5: Determine Top GSI Solution for Each Segment

The last four steps score potential GSI solutions for a given functional roadway classification (Step 1), rank the implementation preference of GSI types (Step 2), compute the required space for a given type of GSI (Step 3), and calculate the space available in the ROW for a series of roadway modification scenarios (Step 4). The last step in determining the top solution uses an iterative process (Figure 17) to compare the space available in each

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[1] The furniture zone, or amenity zone, is the area between the back of curb and sidewalk that is typically reserved for utilities or other street furnishings. The clear zone is adjacent to the furniture zone and must remain unobstructed to allow for pedestrian access.

roadway modification scenario (Table 9) to the required space for each type of GSI. In general, the top solution minimizes roadway modifications while maximizing GSI score.

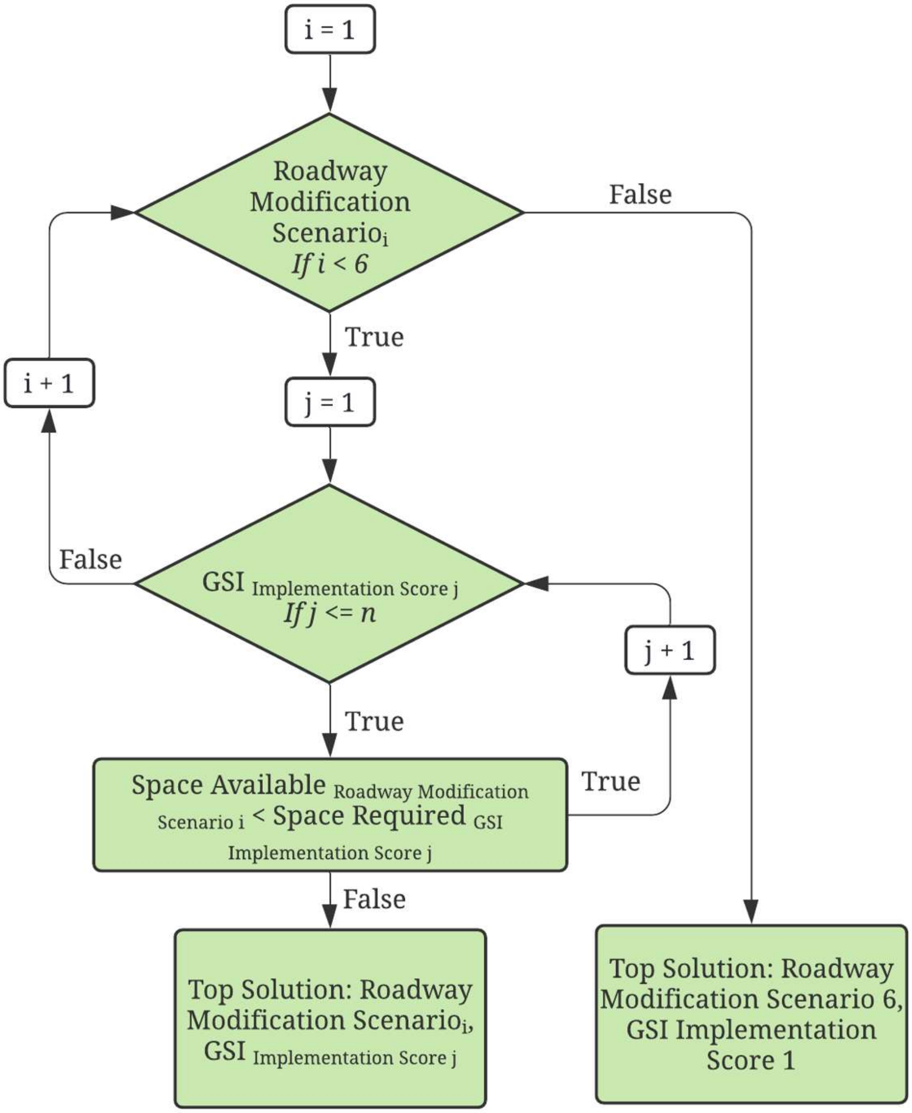


Figure 17 – Top GSI solution process diagram

To minimize potential disturbance to the roadway and maximize feasibility, the top solution prioritizes roadway modification scenarios before GSI preference. In the first iteration, the space available in roadway modification scenario 1 (no change to the existing roadway) is compared to the space required by highest scoring GSI (bioretention). If the space available in the ROW is *greater than* the space required for the GSI, then there is adequate space in the ROW and the top solution is determined. If the space available is *less than* the space required, the next highest scoring GSI-type is considered. Once all GSI-types have been exhausted for a particular segment under the first roadway modification scenario, the next roadway modification scenario is examined, again cycling through GSI types in order of implementation score to compare space available against space required. If the space in the ROW is deemed inadequate for the first five roadway modification scenarios, the default solution becomes roadway modification scenario 6 (complete reconfiguration).

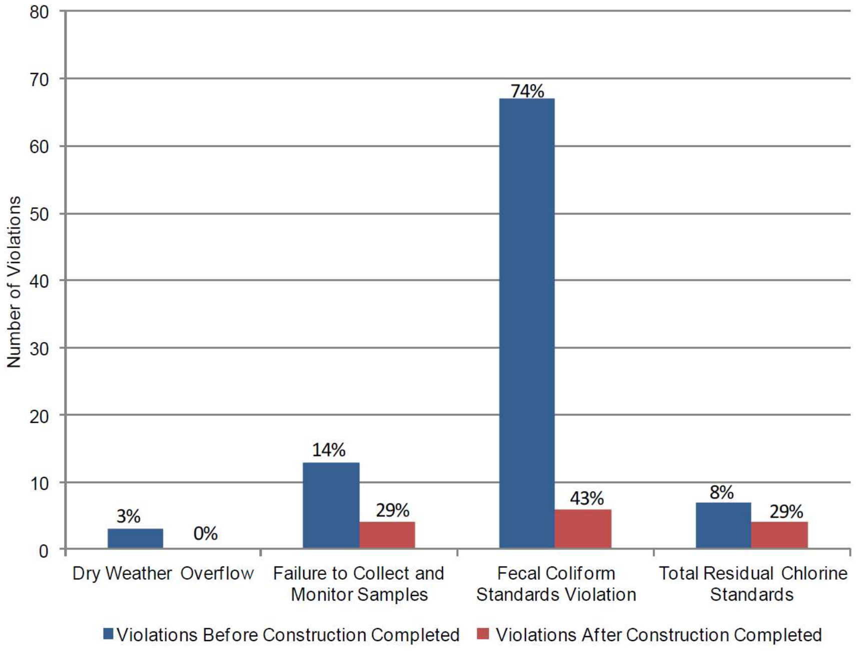
This method is carried out for all three design storms to determine at the top GSI solution for each segment. CHAPTER 4, which is specific to the City of Atlanta, utilizes this process to propose GSI across the study area.

CHAPTER 4. ATLANTA CASE STUDY

4.1 Background

The City of Atlanta provides the perfect lens with which to view the potential benefits that a programmatic green streets policy can provide. While the city has been utilizing GSI in its private development projects for over a decade, there has not yet been a systematic approach to incorporate facilities into public linear construction projects. Atlanta's CSO and flooding problems are no secret, and even after decades of sewer improvements, the city is yet to fully satisfy the requirements of their NPDES permit. A 1994 article published in the Atlanta Journal Constitution alerted the public to widespread issues by claiming that the city had "one of the worst sewer systems in the country" (1) and was regularly experiencing overflows that were in direct violation of the CWA. At the time, CSOs repeatedly washed tons of raw sewage into the city's public parks, an amount great enough to fill 220 Olympic-sized swimming pools (Hallum 1994). Downstream communities as far as 65 miles away were also taking notice as their own water sources suffered from Atlanta's discharge upstream, which was rife with contaminants (Hallum 1994).

Just four years after the article was published, the United States took legal action against the city by issuing a federal Consent Decree, which put forth two main requirements: First, that Atlanta become fully compliant with NPDES permits, the Georgia Water Quality Control Act, and the CWA for CSO control facilities, and second, the city must eliminate all unpermitted discharges from the combined sewer system (CSS) (US EPA 2018). The Consent Decree also stipulated any fees that would be administered given future NPDES violations, which by 2013 had amounted to over $740,000, plus an additional $3M from previous violations (City of Atlanta 2014). After an initial round of sewer improvements were completed in 2008, a 2014 performance audit conducted by the City of Atlanta found that the city had successfully decreased average water quality violations by 65%. Figure 18 shows the violations and their relative frequency before and after Consent Decree-related sewer improvements were completed. To date, Atlanta has completed approximately 72% of its promised sewer improvements and remains on schedule to deliver all outstanding Consent Decree-related sewer projects by the 2027 completion deadline (US EPA 2018).



Source: Department of Watershed Management staff

Figure 18 – Number and percent share of water quality violations by type, July 1998 – July 2013
(City of Atlanta, 2014)

While Atlanta has made vast improvements to the existing CSS, NPDES violations and deferred maintenance continue to threaten ongoing compliance. From 2001 to 2017, there have been an average of eight NPDES violations per year, with significant increases during wetter years (2001, 2006, 2015) (US EPA 2018). In addition, the city has an estimated $25M-$36M in deferred maintenance costs (City of Atlanta 2014). As of 2017, Atlanta has spent approximately $1.07B of its $1.9B allotted to updating the CSS, which includes partial separation in some combined sewer areas (CSAs). However, the increasing rate of development within densely populated areas has sparked uncertainty as to whether Atlanta can ever achieve 100% compliance with their consent decree, and ultimately the CWA.

4.1.1 Combined Sewer System

Atlanta's wastewater collection system serves an area of approximately 225 square miles, which includes the City of Atlanta and some outlying areas (City of Atlanta 2011). The combined sewer system makes up approximately 10% of the wastewater collection system and services approximately 11 square miles in the densely developed core of the city, including downtown and midtown (City of Atlanta 2014). The Atlanta Department of Watershed Management (DWM) was formed in 2002 and is responsible for operating and maintaining all public sewers, including the combined portion, which contains approximately 86 miles of combined sewer pipe within the 11 square mile service area.

The collection system is mostly comprised of brick or concrete pipes that range from 8-inches to 11-feet in diameter (City of Atlanta 2011). In addition to the general collection and conveyance pipes, the DWM operates six combined sewer overflow facilities and three water reclamation (WRC) centers. Water reclamation centers collect and treat wastewater in accordance with Consent Decree standards and release fully-treated water into nearby water bodies, such as the Chattahoochee River (City of Atlanta DWM 2010). There are two additional CSO facilities, Greensferry and McDaniel, that have been decommissioned and replaced with separate sewer systems per Consent Decree requirements. The projects, which were completed in 2008, decreased water quality violations in both number and severity (City of Atlanta 2014). Therefore, the remainder of this section focuses only on the six CSO facilities that remain in operation, which continue to threaten EPA compliance and pose ongoing risks to public health. Figure 19 shows the remaining CSO facilities and their associated combined sewer treatment basins.

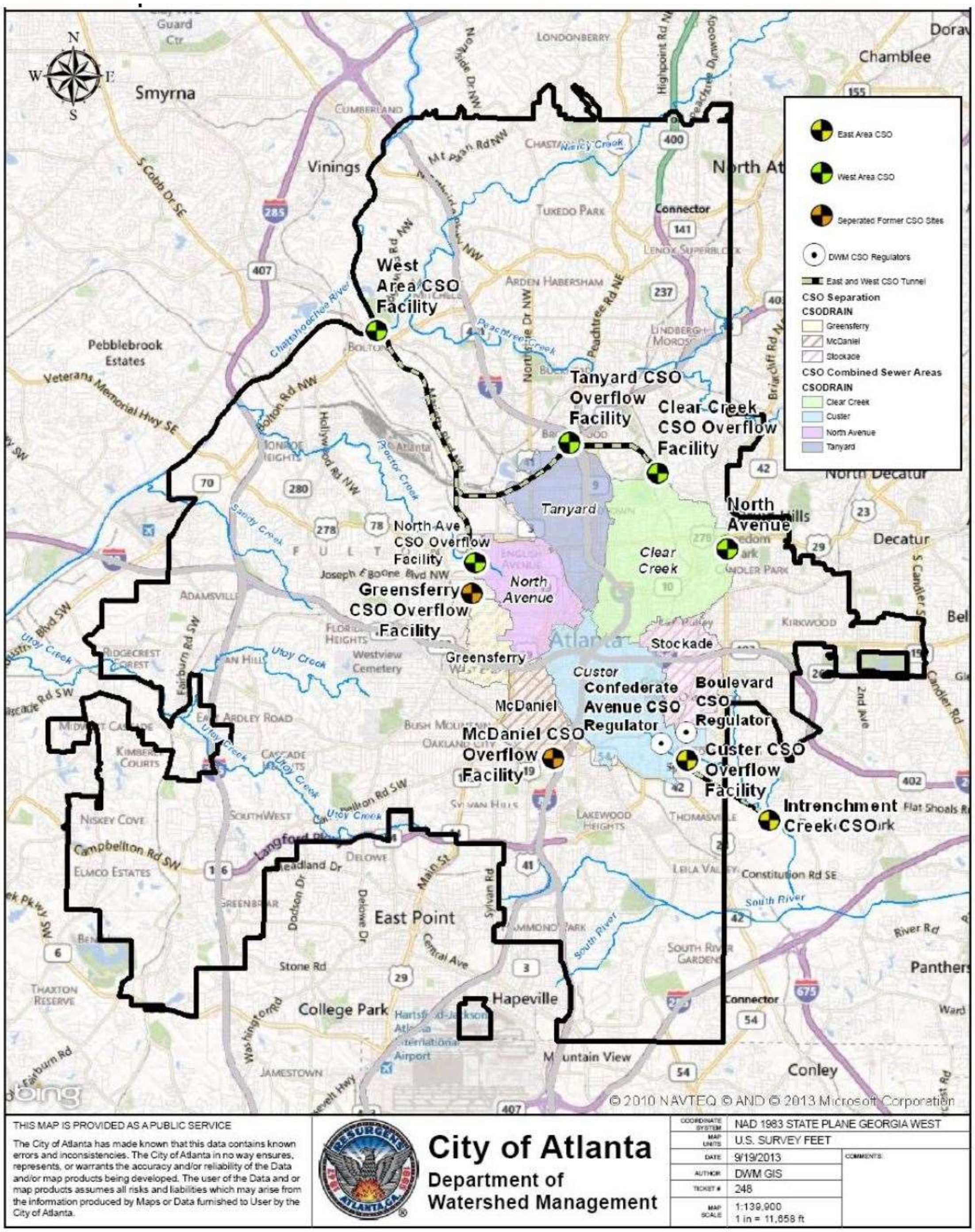


Figure 19 – City of Atlanta combined sewer overflow facilities and sewer basins (City of Atlanta DWM Engineering Division, 2014)

In general, CSO facilities are divided into east and west areas, which correspond with the ultimate drainage basin of the CSO outfall. The Chattahoochee River Basin accepts all discharge from West Area CSOs, while the Ocmulgee River Basin and its tributaries (e.g., South River) accept discharge from East Area CSOs. The left-hand panel of Figure 20 shows the water treatment process for wet weather flows in West Area CSOs. The first point of treatment is the R.M. Clayton WRC. Runoff is directed to the West Area CSO system when the WRC reaches capacity and is then distributed via the West Area Tunnel to the four CSO facilities (West Area, North Avenue, Tanyard Creek, and Clear Creek). The West Area Tunnel, which is approximately 200 feet deep, 8.5 miles long, and 26 feet in diameter, offers additional storage capacity during rain events (City of Atlanta 2014). During an extreme rain event, CSO capacity may also become overwhelmed, causing the discharge of minimally treated wastewater to nearby creeks (Peachtree, Proctor, Tanyard, or Clear). During dry weather, the process operates in reverse, as water is collected by the CSOs, then conveyed back to R.M. Clayton where it receives proper treatment and gets released directly into the Chattahoochee River.

In the East Area CSOs, depicted on Figure 19's right-hand panel, wastewater is initially treated at the Intrenchment Creek WRC. Once capacity is reached, combined sewer flows are diverted to the Boulevard Regulator where they are treated with chlorine and directed to the Custer Avenue CSO. If the Custer Avenue CSO reaches capacity, wastewater is again diverted to a storage facility, then ultimately to the Intrenchment Creek CSO via the Intrenchment Creek Tunnel. Much like the West Area Tunnel, the 1.8-mile long Intrenchment Creek Tunnel serves as extra storage during an extreme rain event, with a capacity of 44 million gallons (City of Atlanta 2014). CSO facilities in the East Area discharge into Intrenchment Creek, which ultimately flows to the South River. During extreme rain events, the Custer Avenue CSO may discharge directly into Intrenchment Creek with minimal treatment. During dry weather periods, flows are treated in the Intrenchment Creek CSO, then the South River WRC, before they are released into the Chattahoochee River (City of Atlanta 2014).

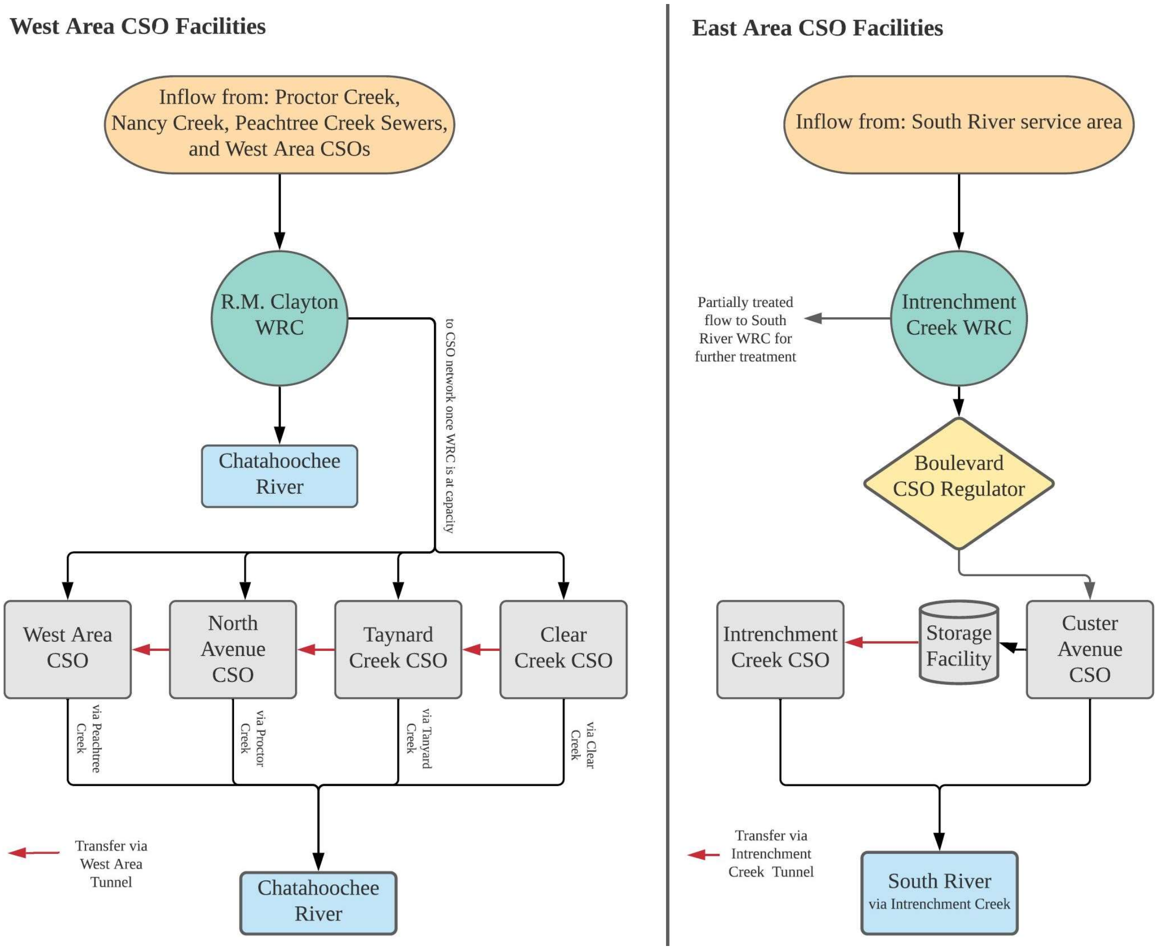


Figure 20 – Atlanta CSO water treatment process for wet weather
(Adapted from "Performance Audit: Combined Sewer Overflow Consent Decree Impact" by City of Atlanta, 2014, p. 7.)

While CSOs, tunnels, and storage facilities have greatly increased system capacity and reduced CSO-related pollution, rain events with extended duration or high intensity continue to release minimally treated sewage into Atlanta's waterways. From 2015 to 2020, seven wet weather CSO spills were documented from the West and East Area CSOs. Routine testing at CSO facilities also reveals 19 instances over the past five years in which fecal coliform levels exceeded permitted limits. Fecal coliform is a common bacterium derived from human or animal feces that threatens public health when found in water sources used for drinking or recreation (US EPA 2012). Furthermore, although the issue is not directly detailed in DWM reports, frequent local flooding within the CSA necessitates roadway closures, can damage property, and greatly strains existing infrastructure. Every year, DWM receives approximately 1300 stormwater-related complaints from across the city, many of which are related to damaged infrastructure and street flooding. Figure 21 maps the complaints fielded by DWM from 2004-2016 where several clusters appear in the CSA.

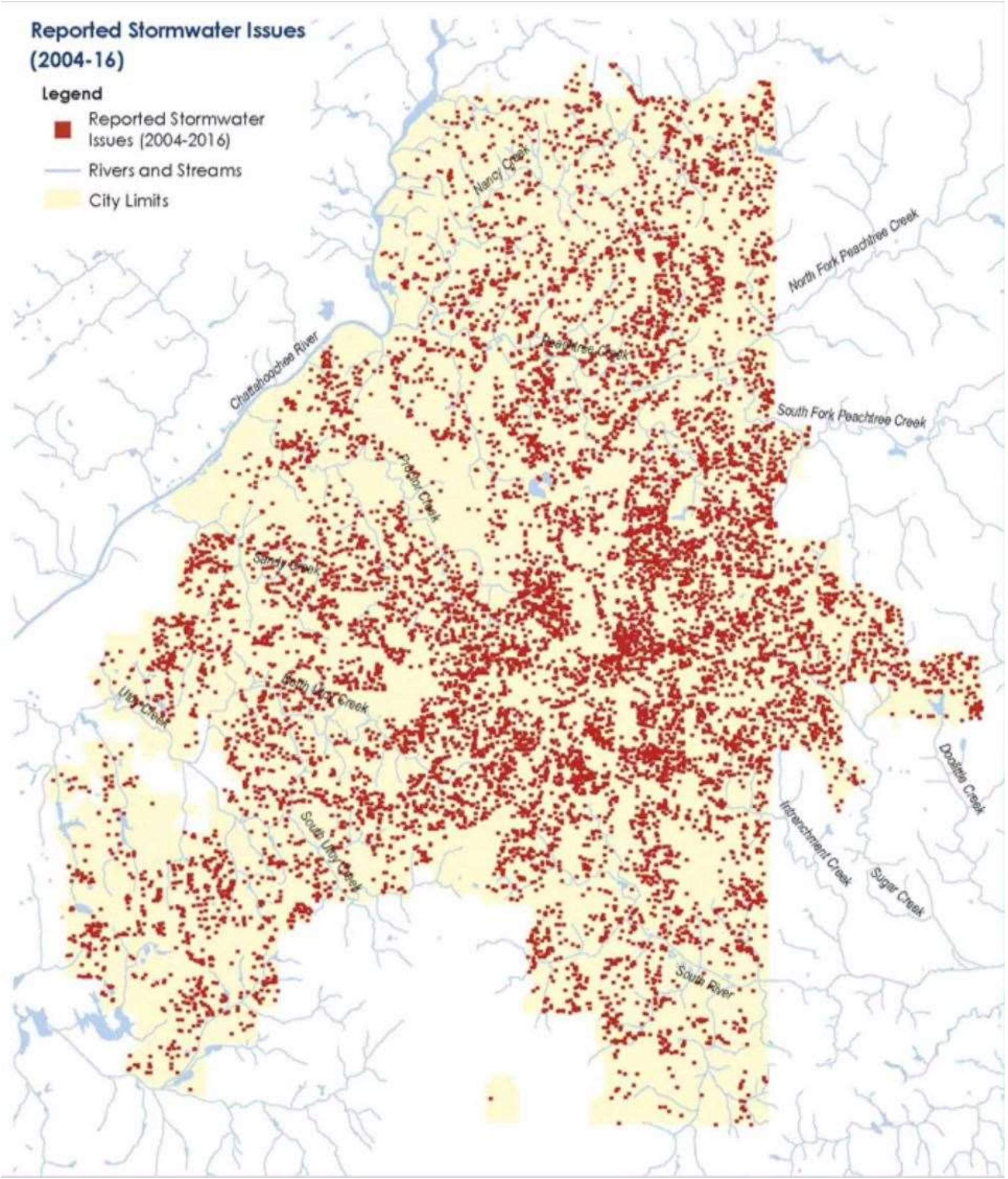


Figure 21 – Reported stormwater issues 2004-2016
(City of Atlanta, Department of Watershed Management, 2020)

According to DWM, decisions for capital projects are first driven by Consent Decree requirements, and second by complaints received (Rutherford 2020). Over the past decade, DWM has attempted to shift Atlanta's stormwater management program from reactive to proactive through policy that focuses on GSI strategies rather than conventional gray solutions.

4.1.2 GSI Planning Initiatives

In the last 15 years, The City of Atlanta has engaged in several GSI inspired planning efforts. The Post-Development Stormwater Management Ordinance (Chapter 74, Article X) was released in 2013 by the City of Atlanta Department of Watershed Management (DWM) and applies green infrastructure standards to commercial and single-family residential development. The ordinance requires new developments (or redevelopments) over 500 square feet to utilize GSI to collect and treat the first inch of rainwater that falls on their site (City of Atlanta DWM 2020b). Recently, the city has expressed interest in adopting a linear construction component within the Ordinance. If adopted, the Ordinance would require any transportation project over 5,000 square feet to capture the first inch of runoff using GSI (City of Atlanta DWM 2020b). However, the process for incorporating GSI into linear projects remains unclear, both in terms of design and financing. The policy allows partial exemptions for several conditions that are extremely likely in nearly every urban scenario, including the following (City of Atlanta DWM 2020b):

1. Where implementation requires relocation of utilities or other structures
2. Where steep topology or other geological features exist, such as high groundwater table or shallow bedrock, or if the area is highly contaminated

3. Where installation of BMPs is an economic hardship due to ROW acquisition, construction, or relocation of utilities solely for the construction of BMPs

Although there will undoubtedly be scenarios that could warrant some level of exemption, US cities have demonstrated they can consistently incorporate GSI into most urban projects, regardless of existing conditions. Prior to implementation of the linear construction policy, the city must anticipate a variety of probable issues and provide adequate design guidance to minimize potential for a project to be deemed infeasible.

Whereas the post development ordinance addresses the use of GSI within private development projects, the 2018 Green Infrastructure Strategic Action Plan provides a systematic planning framework for *all* development projects, including those in the public ROW. The framework lists several objectives that must be met prior to implementation of a formal policy, including evaluation of project funding, development of GSI-related technical specifications, post-construction monitoring, and an understanding of existing conditions (City of Atlanta DWM 2018). The Strategic Plan was compiled under the guidance of the City's green infrastructure task force, a group of eight City of Atlanta agencies and several private stakeholders. The task force laid the foundation for the cross-bureau coordination required for efficient planning, construction, and maintenance of GSI, but the Strategic Action Plan only provides the first step to implementing a comprehensive GSI policy.

Although a comprehensive GSI policy inclusive of both public and private development is yet to materialize, existing policies have contributed to several Atlanta-based GSI projects over the past decade. Two of the most prominent public GSI projects include Historic Fourth Ward Park (Figure 22) and the Peoplestown permeable paver retrofit. Historic Fourth Ward Park, a 17-acre public park located in the heart of Atlanta, is perhaps the city's most visible installment of GSI to date (Historic Fourth Ward Park Conservancy 2020). The park features a constructed detention pond which temporarily detains the 100-year storm to relieve the surrounding 800-acre drainage basin from overflows, and reduce peaks flow to the combined sewer (Historic Fourth Ward Park Conservancy 2020). Not only does the park provide obvious co-benefits, such as an aesthetically pleasing environment for recreation and gathering, but it also provides environmental benefits such as ecosystem restoration and habitat creation. Best of all, the green solution cost $15M less than the conventional gray solution, a shining example of the potential economic advantage of GSI (City of Atlanta DWM 2018).

Figure 22 – Historic Fourth Ward Park detention pond
(City of Atlanta, Department of Watershed Management, 2020)

The Peoplestown permeable paver project in the Custer CSO basin provides much-needed relief for frequent flooding in the south Atlanta neighborhood. The project replaced approximately 6-miles of conventional asphalt roadway with curb to curb permeable pavers to provide temporary detention of stormwater runoff. Atlanta DWM, who oversaw the project, cited several challenges related to installation, the most problematic of which was the relocation of existing utilities (Rayburn 2020). Steep roadway slopes also necessitated the use of check dams within the underground detention component, which decrease flow rates while maintaining the structural integrity of the permeable paver system to combat a heavy rain event (Rayburn 2016). The paver system can detain a 25-year storm, well beyond the volume required by the proposed linear construction ordinance. While localized flooding may still occur during large storms, the project has demonstrated success in relieving local flooding issues within the ROW during frequent storms.

Atlanta's existing GSI policies have impacted over 5,000 public and private projects across the city since 2013 (City of Atlanta DWM 2020a). Private projects alone remove roughly one billion gallons of stormwater from the public sewer system annually and accept runoff from over 1,300 acres of impervious surfaces (City of Atlanta DWM 2020a). While current policies sufficiently address private development, design guidance and general project support are needed before a successful GSI program can be systematically implemented in the public realm.

4.2 Existing Conditions Assessment

4.2.1 *Study Area*

As of 2022, there are four CSA sheds within Atlanta city limits (Figure 23) and all other sewer sheds were previously separated per Atlanta's Consent Decree requirements. CSA shed data was retrieved from the City of Atlanta Department of Watershed Management (DWM) and imported an into ArcGIS for analysis.

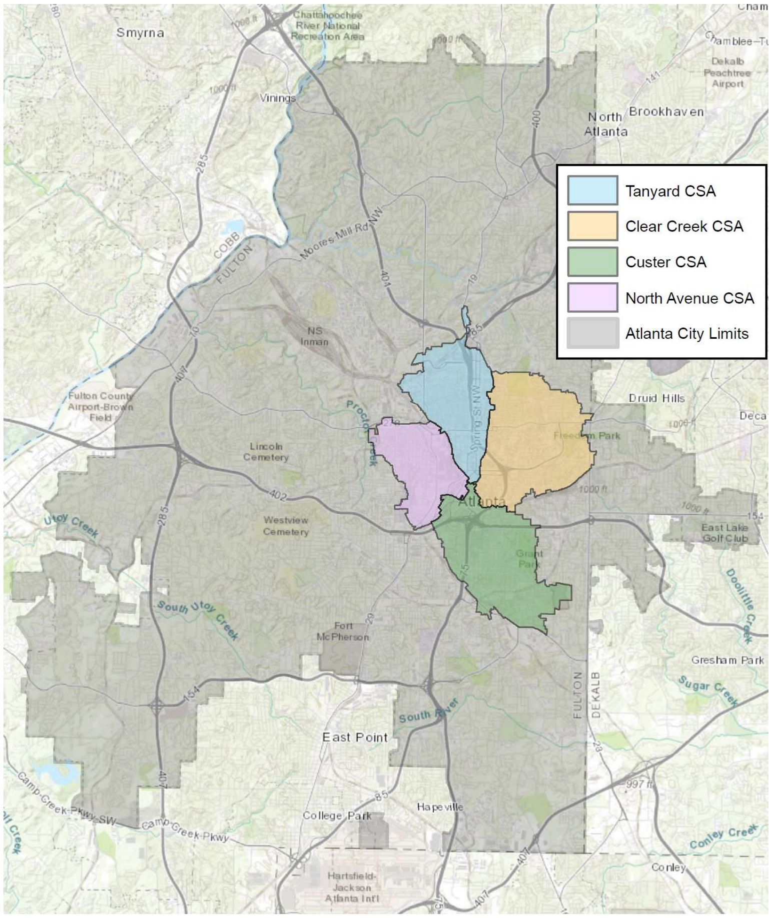


Figure 23 – Combined sewer areas within the City of Atlanta

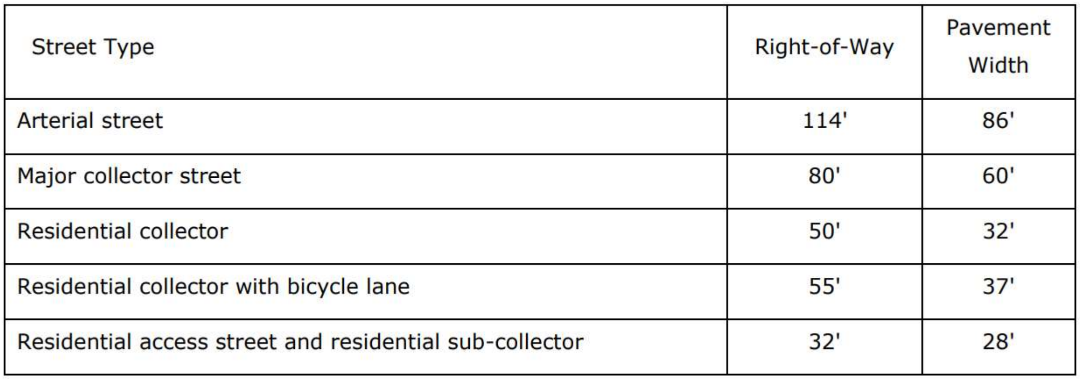
The study area is further defined by overlaying roadway information onto the CSA areas. The City of Atlanta does not have a publicly accessible database of roadways, so the statewide Georgia Department of Transportation (GDOT) roadway inventory was utilized. The GDOT inventory, which was last updated in 2019, contains information for every roadway segment in the State of Georgia. Each segment contains a unique route ID, ownership information, functional classification, and roadway geometry. Segments were trimmed in ArcGIS to include only those that fell within CSA areas. Interstates and major freeways were removed from the dataset as well as any duplicate segments and segments with overlapping geometry were edited to form a single, continuous path.

4.2.2 Right-of-Way Information

Next, roadway geometry was reviewed and verified for all segments within the study area. Initial inspection of the data uncovered major discrepancies between the roadway width stated in the inventory versus the width measured in Google Earth. It is imperative that roadway widths reflect existing conditions because this analysis bases stormwater runoff calculations on the area of the roadway. Thus, the source of truth for width in this analysis required manual input from maps provided by Google Earth. Segments with large variations in roadway width were broken into multiple segments to better reflect their true width. Lane types and total number of lanes per GDOT's inventory were also reviewed and corrected using Google Earth as necessary. Finally, segments greater than 500 feet in length were broken into shorter segments to better depict drainage areas that exist within an urban area.

ROW widths were then manually associated with each segment via a combination of historical plats and cadastral maps available through the City of Atlanta's GIS website. The historical plats and cadastral maps show legal lot boundaries, and although they sometimes contained conflicting information, the data provided a rough estimate for ROW widths, which provided adequate material for a planning-level analysis. Any segment that did not have a corresponding plat or cadastral map (<5% of segments) was assigned a width based on roadway typologies and widths retrieved from the City of Atlanta Right of Way Manual (Table 10). In some instances, ROW width was less than the measured roadway width. In these instances, the ROW boundary was assumed to coincide with the back edge of the sidewalk located on either side of the street.

Table 10 – ROW widths per the City of Atlanta ROW Manual



Street Type	Right-of-Way	Pavement Width
Arterial street	114'	86'
Major collector street	80'	60'
Residential collector	50'	32'
Residential collector with bicycle lane	55'	37'
Residential access street and residential sub-collector	32'	28'

Stakeholder information provided by GDOT was also reviewed and Figure 24 shows the roadways within the scope area owned by GDOT versus the City of Atlanta. Since most roadways within the scope area fall within the City of Atlanta's jurisdiction (approximately 240 miles versus GDOT's 17 miles), the remainder of this analysis focuses on standards and specifications set forth by the City of Atlanta.

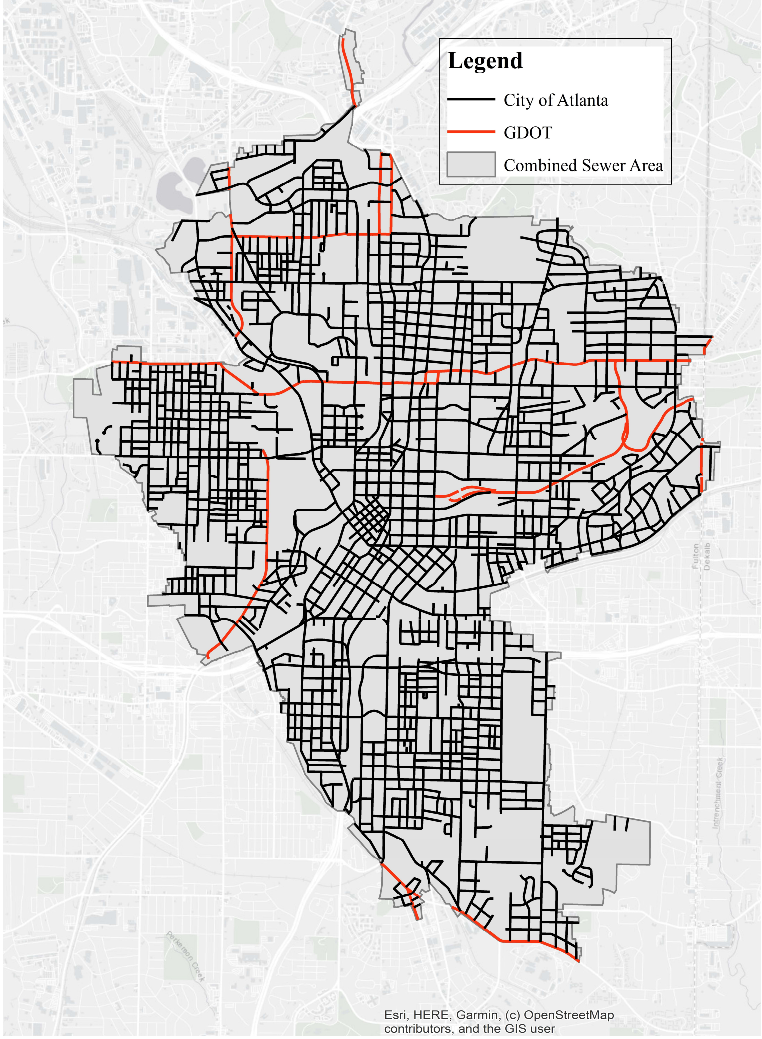


Figure 24 – Roadway jurisdictions within Atlanta's combined sewer area

4.2.3 Supplementary Data

After existing conditions data from GDOT was verified, zoning classifications were overlaid on the study area and associated with each roadway segment. Zoning dictates minimum sidewalk widths per functional roadway classification. For most zoning types, the minimum sidewalk width is five feet (5.0’) for local and collector roads, and ten feet (10.0’) for arterial roads. The City of Atlanta breaks the sidewalk into two zones, the street furniture zone and the clear zone. The furniture zone is located immediately adjacent to the back of curb and may be utilized for GSI. The clear zone is located adjacent to the furniture zone and must remain unobstructed to allow for pedestrian access (City of Atlanta 2022). Neighborhood boundaries, as defined by the Atlanta Regional Commission were also associated with each segment in the dataset

4.3 Runoff Calculations

Once the dataset was cleaned and finalized, runoff calculations were performed per the methodology outlined in Section 3.2.

4.3.1 Water Quality Volume Scenario

Eq. (1) from Section 3.2.1 calculates the water quality volume (WQ_v) associated with each segment. To calculate R_v, the percentage of impervious area (I) must be determined for each segment. Since segment area coincides with paved roadway area, it can be assumed that I is equal to 100 for all calculations, and thus, R_v is constant. Therefore:

$$R_v = 0.05 + 0.009(100) = 0.95$$

Area is calculated as the length of a given segment multiplied by the roadway pavement width per eq. (15):

$$A_{segment\ i}(SF) = Length_{segment\ i}(FT)\ x\ Roadway\ Width_{segment\ i}(FT) \tag{15}$$

Then,

$$WQ_{V,segment\ i} = \frac{1.2 * 0.95 * \ A_{segment\ i}}{12} \tag{16}$$

Eq. (16) is applied to the study area to calculate the water quality volume (WQ_v) for each segment. Individual segment calculations are provided in the supplementary dataset submitted with this research, and further discussion of results can be found in Section 4.5.1.

4.3.2 25-Year, 24-Hour Storm Scenario

This section follows the steps outlined in section 3.2.2 to calculate the runoff generated by a 25-year, 24-hour storm in the City of Atlanta.

4.3.2.1 Steps 1-3: Determine Rainfall (*P*), Runoff Curve Number (*CN*), and Direct Runoff (*Q*) for the 25-Year, 24-Hour Storm Event

Accumulated rainfall (*P*) for Atlanta (Appendix B) is calculated using an Atlanta-specific rainfall intensity table provided by the GSMM. For a 25-year storm with a duration of 24-hours results in a rainfall intensity (*i*) of 0.27 inches / hour. Eq. (2) calculates the total accumulated rainfall:

$$P_{25} = 0.27\frac{in}{hr}x\ 24\ hr = 6.48\ inches$$

Eq. (4) is used to calculate potential maximum soil retention (*S*). First, the curve number (*CN*) must be defined. Per Table 2.1.5-1 from the GSMM (Appendix B), the *CN* for impervious areas is 98, regardless of soil type. Therefore:

$$S = \frac{1000}{98} - 10 = 0.204\ inches$$

Finally, the direct runoff (Q_d) can be calculated with known values for *P* and *S* using eq. (6) from section 3.2.2.3.

$$Q_{d\ 25} = \frac{(6.48 - 0.2(204))^2}{6.48 + 0.8(.204)} = 6.24\ inches$$

4.3.2.2 Step 4: Determine Time of Concentration (T_c) for the Development Site (Pre-Development conditions)

T_l is calculated for each segment using eq. (7). Per Section 3.2.2.4, the Manning roughness coefficient (*n*) equals 0.11, flow length (*L*) is the measured width of each roadway segment, and land slope (*S*) is assumed to be 2% for all segments. A slope of 2% is consistent with roadway grading requirements set forth by the City of Atlanta and GDOT. Finally, P_2 is retrieved by multiplying the intensity found in Table A-2 for a 2-year, 24-hour storm by 24 hours.

P_2 = 0.17 in/hr x 24 hr = 4.08 inches

With all variables known, T_1 can be defined by the following equation for any given segment:

$$T_{1,segment\ i}(hr) = \frac{0.42\left(0.011 * L_{segment\ i}\right)^{0.8}}{60(4.08)^{0.5}(.02)^{0.4}} \tag{17}$$

Individual results for T_1 revealed short times of concentration as anticipated. Since values for T_1 were relatively small and there were many instances where T_1 was zero, units were converted into minutes, with values ranging from 0.17 minutes to 1.19 minutes. The supplementary dataset submitted with this research provides detailed calculations.

T_2, which represents shallow concentrated flow, is then calculated using eq. (8) and eq. (9). Watercourse slope (*S*), which refers to the longitudinal slope of the roadway, is assumed to be 2% for all segments. Topography can vary significantly throughout Atlanta and while a value of 2% may not be reflective of every segment's existing conditions, it is within the range of allowable longitudinal slopes for urban areas according to GDOT's Design Policy Manual (GDOT 2022). Flow length (*L*) corresponds to the length of each segment. T_2 can then be defined as the following for any given segment:

$$T_{2,segment\ i} = \frac{L_{segment\ i}}{3600 * 20.33(.02)^{0.5}} \tag{18}$$

T_2 was calculated for all segments and converted to minutes. Values varied from 0 minutes for shorter segments to 2.9 minutes for segments that were approximately 500 feet (see supplementary dataset for details).

The total time of concentration (T_c) for each segment was then calculated by summing the two travel times, T_1 and T_2, and results varied from 0.27 minutes to just over four minutes. Compared to a typical small land development project, the times of concentration are extremely short, while an analysis for a larger drainage area with a variety of surface treatments (e.g., landscaping, unpaved areas, etc.) could have a time of concentration that ranges from 5 minutes to an hour. However, the range of values is typical for small urban areas, especially when the drainage area mainly consists of paved surfaces. The GSMM acknowledges the fact that time of concentration will be shorter for urban scenarios and recommends using a minimum of five minutes. Since the time of concentration for all segments resulted in a duration of less than five minutes, T_c for all future computations is assumed to equal five minutes for all calculations

4.3.2.3 Step 5: Compute Peak Discharge, (Q_p, Pre-Development Condition)

Eq. (10) is used to calculate the peak discharge for each segment. First, unit discharge (q_u) is retrieved from Figures 4 and 5 in Section 3.2.2.5. The units for q_u are csm/in, which represents cubic feet per second (cfs) per square mile (mi^2) of drainage area per inch of runoff (in). Figure 4 shows that Atlanta falls within a Type II Rainfall Distribution, which informs the use of Figure 5. The Unit Peak Discharge Graph first requires the calculation of $\frac{Ia}{P}$ using the values calculated in previous steps:

$$\frac{I_a}{P} = \frac{0.408}{6.48} = 0.006$$

GSMM recommends using the limiting $\frac{I_a}{P}$ line if values do not align with those shown in the graph. Therefore, the limiting line of $\frac{I_a}{P}$ = 0.1 is used for this scenario. Given that T_c = ~0.1 hours and $\frac{I_a}{P}$ = 0.1, the unit discharge (q_u) is 1000 cfs/mi^2/in.

Area (A) is defined as the segment area in square miles and runoff (Q) was calculated in Section 4.3.2.1. The pond adjustment factor (F_p) is retrieved from Table 2, and because there are no pond and swamp areas within the drainage area defined for each segment, F_p = 1. Finally, the peak discharge (Q_P) can be calculated for each segment using eq. (19). Q_P values can be found in the supplementary dataset submitted with this research.

$$Q_{P\ 25,segment\ i} = 1000 * A_{segment\ i} * 6.24 * \ 1.00 \tag{19}$$

4.3.2.4 Step 6: Determine the Ratio of Peak Outflow to Peak Inflow ($\frac{q_o}{q_i}$)

Given the peak unit discharge calculated in the previous step, and a known detention time (T) of 24 hours, $\frac{q_o}{q_i}$ is retrieved from Figure 6. When T = 24 hr and q_u = 1000 csm/in, $\frac{q_o}{q_i}$ is approximately 0.02. A value of 0.02 indicates that 98% of the peak runoff for the 25-year, 24-hour storm event will be captured by GSI rather than the combined sewer system. However, this scenario assumes some runoff is detained, not retained, meaning it is eventually released into the combined sewer system. Still, the runoff released to the sewer will enter the system at a much slower rate and during off-peak flows. Retaining 100% of the runoff volume generated by the 25-year, 24-hour storm event is possible if the following requirements are met per City of Atlanta GSI standards (City of Atlanta DWM 2014):

1. The ponding depth of the GSI does not exceed 12 inches
2. The drain-down time (the time for the GSI to drain completely) does not exceed 48 hours

Thus, if infiltration rates of the proposed GSI and underlying soil are extremely favorable, 100% retention is possible.

4.3.2.5 Step 7: Calculate the Ratio of Required Storage Volume to Stormwater Runoff Volume, ($\frac{V_S}{V_r}$)

The ratio of required storage volume to stormwater runoff volume is given by eq. (11) in Section 3.2.2.7 given a value of 0.02 for $\frac{q_o}{q_i}$. Therefore,

$$\frac{V_S}{V_r} = 0.672 - 1.43(0.02) + 1.64(0.02)^2 - 0.804(0.02)^3 = 0.654$$

4.3.2.6 Step 8: Determine the Required Storage Volume *(Vs)*

V_S is calculated using the TR-55 equation for a type II storm per eq. (12) in Section 3.2.2.8. Given that $\frac{V_S}{V_r}$ = 0.654, Q_d = 6.24 inches, and A = segment area (i.e., measured width x length of segment), V_s is calculated for each segment using the following equation:

$$V_{s\ 25,segment\ i}\,(ac - ft) = \frac{0.654 * 6.24 * A_{segment\ i}}{12} \tag{20}$$

V_s represents the storage volume requirement per runoff generated for the 25-year, 24-hour storm. Results are converted to cubic feet for direct comparison with GSI storage to determine how much area GSI demands in the right-of-way to store the required volume. For example, if a segment has a storage volume (V_s) equal to 5000 CF, the GSI area required can be calculated using the estimated CF of storage per SF per Table 4 and eq. (13).

4.3.3 100-Year, 24-Hour Storm Scenario

4.3.3.1 Steps 1-3: Determine Rainfall (*P*), Runoff Curve Number (*CN*), and Direct Runoff (*Q*) for the 100-Year, 24-Hour Storm Event

Accumulated rainfall (*P*) for a 100-year, 24-hour storm event in Atlanta is retrieved from Table A-2 in Appendix B of the GSMM 2001 Edition. For the City of Atlanta, rainfall intensity (*i*) is 0.33 inches / hour, which is utilized in eq. (2) to calculate *P* for the 100-year, 24-hour storm:

$$P_{100} = 0.33 \frac{in}{hr} x\ 24\ hrs = 7.92\ inches$$

The runoff curve number (*CN*) for the 100-year, 24-hour scenario is identical to that of the 25-year, 24-hour scenario. Therefore, *CN* = 98, and *S* = 0.204. The simplified SCS rainfall-runoff equation, eq. (6), is used to determine the runoff (*Q*) generated from the 100-year, 24-hour storm event:

$$Q_{100} = \frac{(7.92 - 0.2(204))^2}{7.92 + 0.8(.204)} = 7.68\ inches$$

4.3.3.2 Step 4: Determine Time of Concentration (T_c) for the Development Site (Pre-Development Conditions)

Since the time of concentration (T_c) is only based on physical characteristics of the drainage area, there is no need to calculate a new value for the 100-year, 24-hour storm. Therefore, the total time of concentration is equal to five minutes per the discussion in Section 4.3.2.2.

4.3.3.3 Step 5: Compute Peak Discharge, (Q_p, Pre-Development Condition)

The pre-development peak discharge given by eq. (10) is used to calculate the peak discharge in the 100-year scenario. Since the value is dependent on the unit discharge, Figure 12 is used with a new value for $\frac{I_a}{P}$ as shown below:

$$\frac{I_a}{P} = \frac{0.408}{7.28} = 0.005$$

As explained in the 25-year calculations, the limiting line ($\frac{I_a}{P}$ = 0.1) will be used. Therefore, q_u = 1000 csm/in, the same value as the previous scenario. Segment area (A) and Pond Adjustment Factor (F_p) also will not change from the 25-year scenario as they are based on physical characteristics of each segment, which are uniform across every scenario. Runoff (Q) can then be defined using the equation below:

$$Q_{P\ 100,segment\ i} = 1000 * A_{segment\ i} * 7.68 * \ 1.00 \qquad (21)$$

4.3.3.4 Step 6: Determine the Ratio of Peak Outflow to Peak Inflow, ($\frac{q_o}{q_i}$)

The ratio of peak outflow to peak inflow ($\frac{q_o}{q_i}$) is needed to determine the storage volume. Since q_u and T_c have not changed from the 25-year scenario, $\frac{q_o}{q_i}$ again equates to 0.02.

4.3.3.5 Step 7: Calculate the Ratio of Required Storage Volume to Stormwater Runoff Volume, ($\frac{V_S}{V_r}$)

Since the ratio of required storage volume to stormwater runoff volume is dependent on the ratio $\frac{q_o}{q_i}$, and the value for the 100-year scenario is the same as the 25-year scenario, $\frac{V_S}{V_r}$ remains 0.654.

4.3.3.6 Step 8: Determine the Required Storage Volume, (Vs)

Finally, Vs is calculated using eq. (11), but this time with a value of 7.68 for Q_d. The storage volume for the 100-year, 24-hour storm is then calculated for each segment as follows:

$$V_{s\,100,segment\ i} = \frac{0.654 * 7.68 * A_{segment\ i}}{12} \tag{22}$$

4.4 Green Street Toolkit Application

The Green Street Toolkit can now be applied using information from the existing conditions assessment and the runoff calculations. Functional classifications associated with each segment are depicted in Figure 25. Within the study area, there are approximately 67 miles of arterial roadways, 29 miles of collector roadways, and 160 miles of local roadways. Table 11 combines data from Tables 3 and 7 to list the appropriate GSI types for each classification in order of their implementation scores. For example, for an arterial roadway, only bioretention, bioswales, and infiltration trenches are considered, in that order, for the remainder of the analysis.

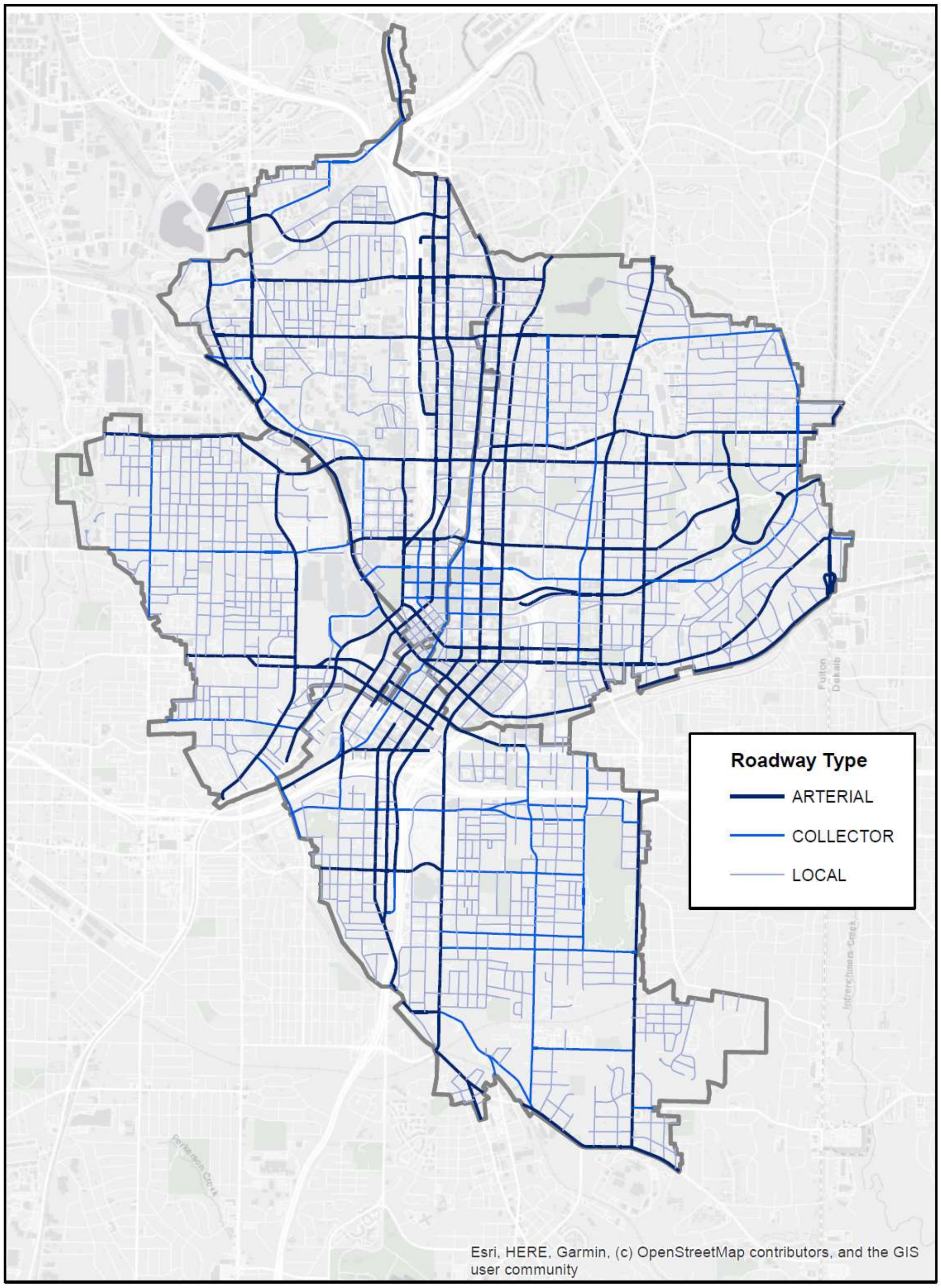
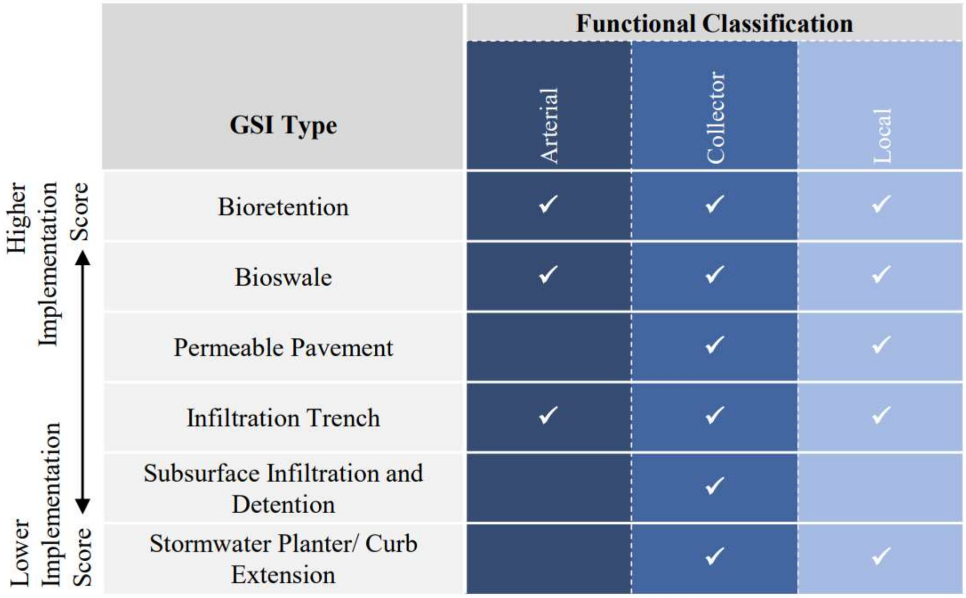


Figure 25 – Functional classification for roadway segments within study area

Table 11 – Appropriate GSI types per functional roadway classification in order of implementation score



Higher Implementation Score ↑ ↓ Lower Implementation Score

GSI Type	Functional Classification		
	Arterial	Collector	Local
Bioretention	✓	✓	✓
Bioswale	✓	✓	✓
Permeable Pavement		✓	✓
Infiltration Trench	✓	✓	✓
Subsurface Infiltration and Detention		✓	
Stormwater Planter/ Curb Extension		✓	✓

Required GSI area is computed for applicable GSI solutions given the available storage (CF storage/SF GSI area) and the required storage (CF) per the runoff calculations. Available area in the ROW is calculated for each modification scenario using roadway geometry data collected in the existing conditions analysis. Required and available area calculations for each segment can be found in the supplementary dataset submitted with this research.

4.5 Results

The top solution for each segment is determined using the iterative process described in Section 3.4.5. A map depicting the best solution, in conjunction with the required roadway modification scenario, is presented for each storm. The ideal solution is heavily skewed toward the top scoring GSI, bioretention, since it is the first type of SCM evaluated in the comparison of required storage volume and required GSI area. Bioretention is also applicable for every roadway classification, has a high storage capacity, and a moderate construction cost – all which lead to its high implementation score (Table 8). Therefore, an additional map is provided which shows the least intensive modification scenario required to accommodate at least three GSI solutions. Although the roadway modification scenarios for the second map may be more intensive in terms of reconstruction, there are more GSI solutions to choose from.

4.5.1 Water Quality Volume Results

The top solutions and accompanying roadway modification scenarios considered for the WQ_v storm scenario are shown in Figure 26, followed by a legend in Table 12. In the WQ_v storm scenario, there are approximately 144 miles of roadway within the study area that do not require modification to the existing roadway to accommodate bioretention, the top GSI solution. Forty-six (46) miles of permeable pavement, the third highest scoring GSI, are also proposed for under the first modification scenario (i.e., no reconfiguration necessary). Altogether, the first roadway modification scenario accommodates at least one GSI solution for nearly 75% of all segments (in terms of miles) within the study area.

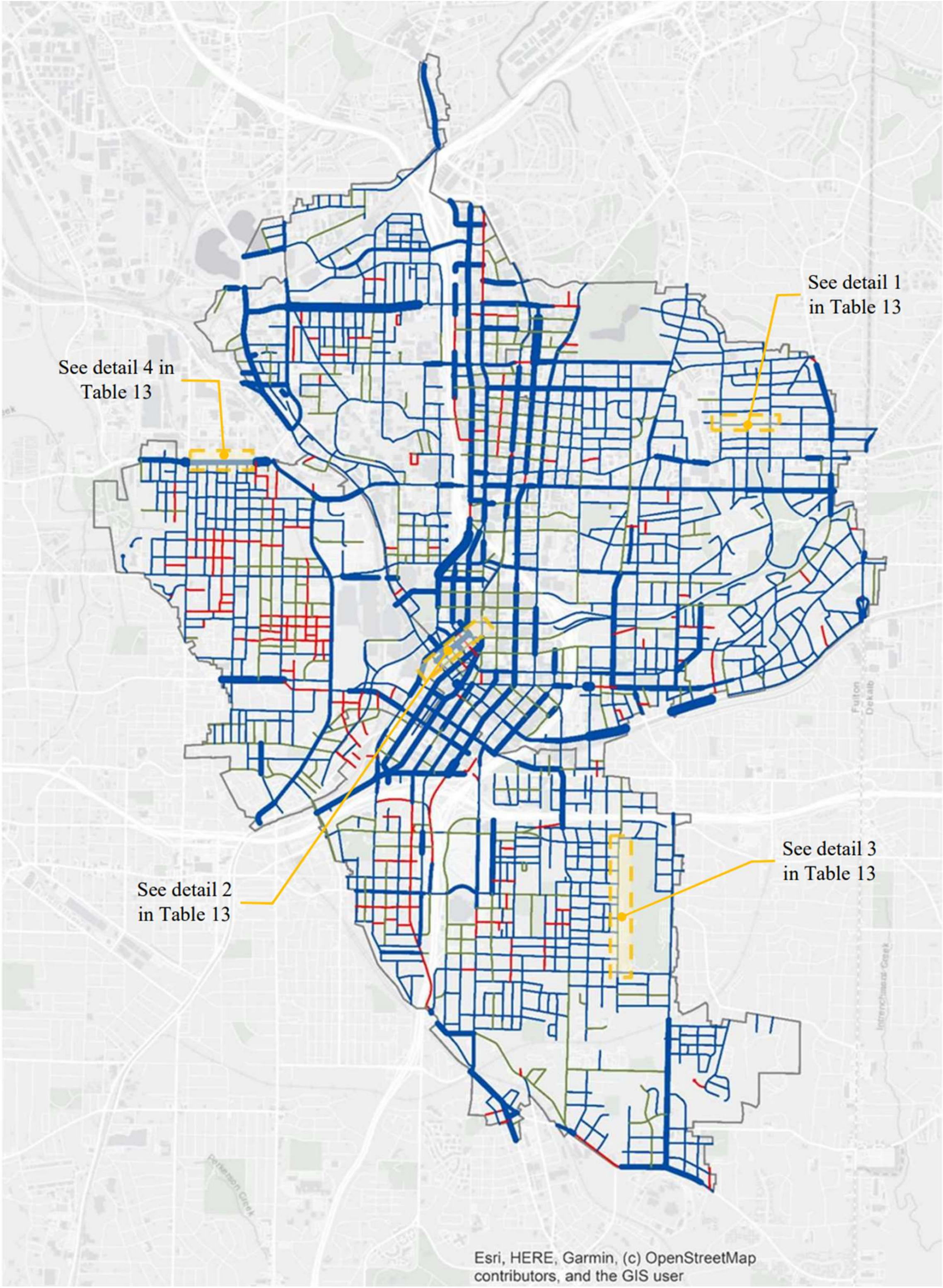


Figure 26 – Top GSI solution vs. roadway modification scenario, WQ_v

Table 12 – Legend: Top GSI solution vs. roadway modification scenario, WQ_v storm scenario

Symbol	Scenario	Solution	# of Segments	Miles
—	1	Bioretention	1879	144.01
—	2	Bioretention	258	18.15
━	3	Bioretention	348	26.32
▬	4	Bioretention	4	0.36
▬	5	Bioretention	27	1.95
—	1	Permeable Pavement	604	45.89
—	6	Major Reconfiguration	277	19.78

Scenarios 2-5, which call for fewer parking lanes and narrower sidewalks, can accommodate at least one type of GSI for 18% of roadways (in terms of miles) in the study area. Many of these segments are in the downtown and midtown neighborhoods, which are the most densely developed areas within the study area. If the recommended roadway modification scenarios are followed for these segments, most of the on-street parking would be eliminated. Fortunately, these areas are also most likely to offer alternative modes of transportation, which supports the argument to remove parking. There are several privately-owned parking lots and garages in the immediate area that could also alleviate the reduction of on-street parking.

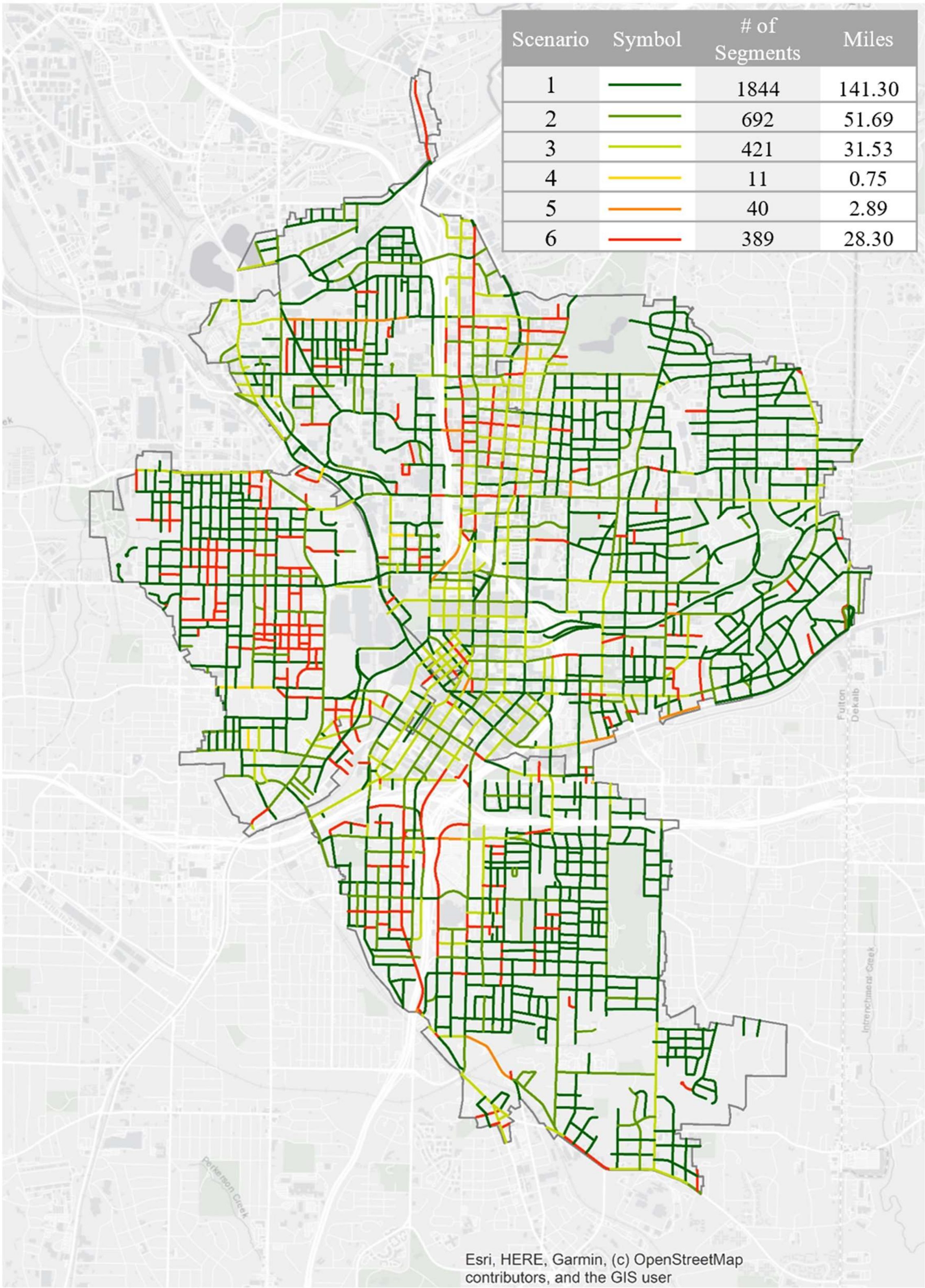
Just under 8% of roadway miles (21.33 miles) require a complete reconfiguration to accommodate at least one type of GSI. Most segments that require a complete reconfiguration are classified as local (73% of roadway miles). Many of these segments have limited ROW space and narrow roadways that cannot accommodate GSI adjacent to the roadway. For local roads that require a full reconfiguration, permeable pavement within the drive lanes may be a viable alternative. Another solution is to utilize adjacent recreational space, such as city parks or plazas, if they exist adjacent to a segment. Intersections can also provide additional space for GSI, particularly when a segment which requires full reconfiguration intersects a segment that requires a lesser roadway modification scenario. There are several alternative solutions that exist for segments that require a full reconfiguration, but each segment must be evaluated on a case-by-case basis to fully examine the existing conditions surrounding the segment area. Table 13 provides an in-depth look at four roadways within the study area of variable classifications. Each detail provides a list of existing conditions, a current photo of the roadway retrieved from Google Maps, the proposed GSI solution, and the associated roadway modification.

Table 13 – Example of GSI solutions and roadway modifications, WQ$_v$ storm scenario

Detail #	Street Name	Street Type	Existing Conditions	Proposed Solution (WQ$_v$)
1	St Charles Ave NE	Local	 ROW Width = 70', Roadway Width = 50', Min Clear Zone = 12', Drive Lanes = 2, Parking Lanes = 2	Reconfig. Scenario = 1 - No Change GSI Type = 1 - Bioretention GSI Width per LF of roadway = 2.8' Drive Lanes = 2 Parking Lanes = 2
2	Cone St NW	Local	 ROW Width = 60', Roadway Width = 40', Min Clear Zone = 16', Drive Lanes = 2, Parking Lanes = 2	Reconfig. Scenario = 3 – Min. Sidewalk Width & Reduce 1 Parking Lane GSI Type = 1 - Bioretention GSI Width per LF of roadway = 2.3' Drive Lanes = 2 Parking Lanes = 2
3	Cherokee Ave SE	Collector	 ROW Width = 60', Roadway Width = 42', Min Clear Zone = 16', Drive Lanes = 2, Parking Lanes = 1, Bike Lanes =1	Reconfig. Scenario = 1 - No Change GSI Type = 3 - Permeable Pavement GSI Width per LF of roadway = 3.4' Drive Lanes = 2 Parking Lanes = 1 Bike Lanes = 1
4	Donald Lee Hollowell Pkwy NW	Arterial	 ROW Width = 60', Roadway Width = 40', Min Clear Zone = 16' , Drive Lanes = 4, Parking Lanes = 0	Reconfig. Scenario = 3, Min. Sidewalk Width GSI Type = 1, Bioretention GSI Width per LF of roadway = 2.2' Drive Lanes = 4 Parking Lanes = 0

Figure 27 shows the least-intensive roadway modification scenario required to accommodate at least three types of GSI. Fifty-five percent (55%) of roadways (in terms of miles) do not require any reconfiguration to accommodate at least three solutions. Another 32% require reduction of one parking lane only, while less than 2% of roadways require elimination of all on-street parking. Eleven percent (11%) of roadways require full reconfiguration to accommodate at least three solutions, but these miles represent a small share of segments within the study area.

For local roads, the first three solutions that accommodate a given modification scenario are bioretention, bioswales, and stormwater planters because they have the highest storage efficiencies, meaning they require the least amount of ROW area per unit volume of runoff stored. For roadways that fall under the collector classification, bioretention, subsurface infiltration and detention, and stormwater planters are the first three solutions to accommodate runoff for a given modification scenario. Arterial roads only have three appropriate types of GSI: bioretention, bioswales, and infiltration trenches. Therefore, for any arterial segment, the minimum roadway modification scenario must accommodate all appropriate solutions.



Scenario	Symbol	# of Segments	Miles
1	🟩	1844	141.30
2	🟩	692	51.69
3	🟩	421	31.53
4	🟨	11	0.75
5	🟧	40	2.89
6	🟥	389	28.30

Figure 27 – Minimum roadway modification scenario required to accommodate at least three GSI solutions, WQ_v

For 99% of segments, the minimum roadway modification scenario that supports at least three GSI solutions can also support the remaining types of GSI proposed in the segment's functional classification. In other words, if a segment classified as local can accommodate bioretention, bioswales, and stormwater planters, it can also accommodate permeable pavement or an infiltration trench. This result is unique to the WQ_v scenario because, compared to the two remaining scenarios, significantly less runoff is produced, and less area is required by GSI. The WQ_v scenario represents approximately 85% of the storms in the Atlanta area, so the results demonstrate a promising path to providing a feasible and flexible green streets approach for a frequent, low-intensity storm.

4.5.2 25-Year,24-Hour Storm Results

Each segment's top GSI solution and associated roadway modification scenario for the 25-year, 24-hour storm scenario is shown in Figure 28 and is accompanied by a legend (Table 13). GSI solutions and roadway modification scenarios are broken down by GSI type and scenario in both Figure 28 and Table 13. There are approximately 107 miles of roadway in the study area that do not require reconfiguration to accommodate bioretention, the top GSI solution. An additional 28 miles of permeable pavement or subsurface infiltration and detention are proposed in the first roadway modification scenario. Therefore, around 53% of roadways in the study area (in terms of miles) can support at least one GSI solution without any modification to the existing roadway configuration.

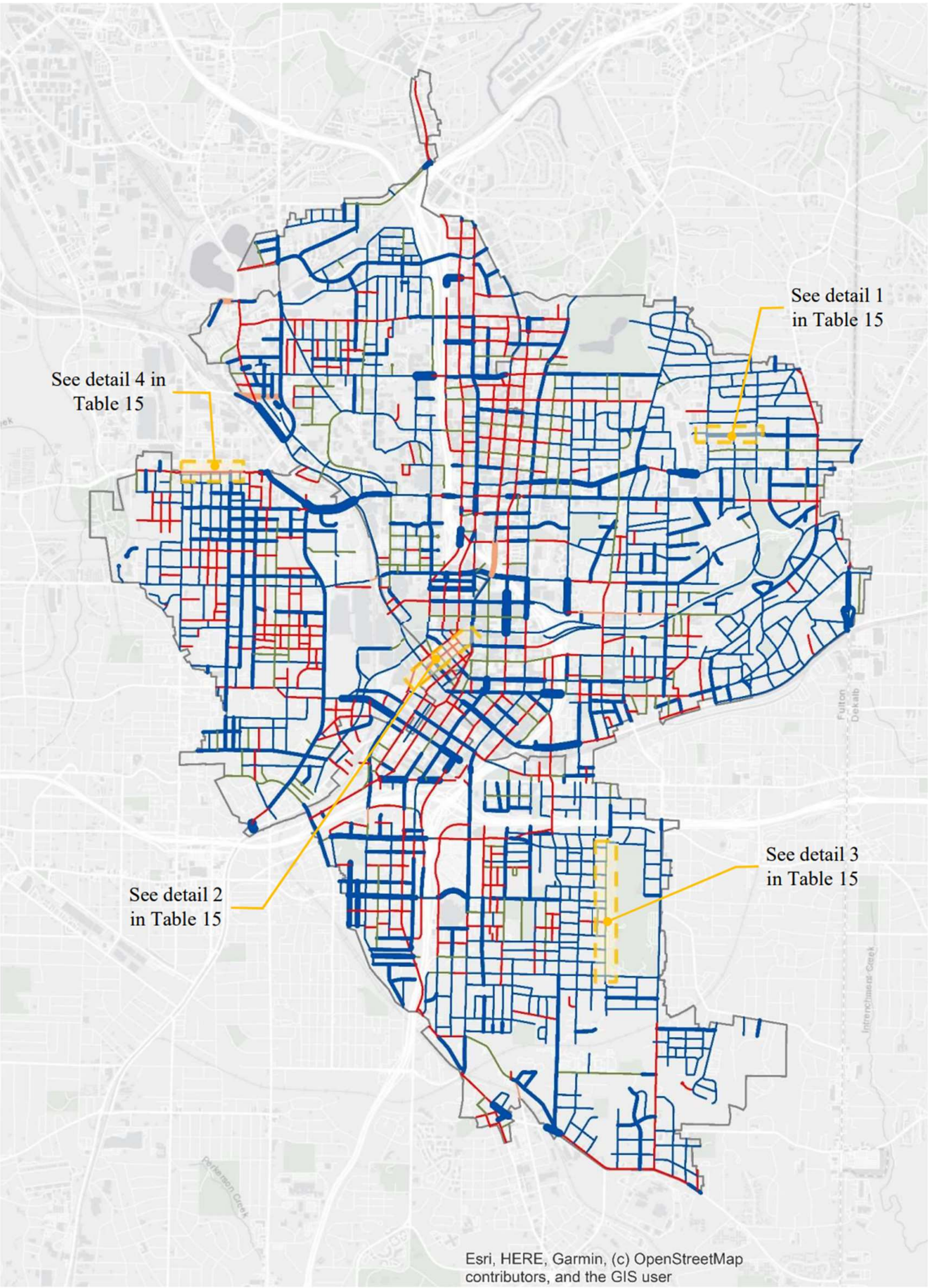


Figure 28 – Top GSI solution vs. roadway modification scenario, 25-year, 24-hour storm

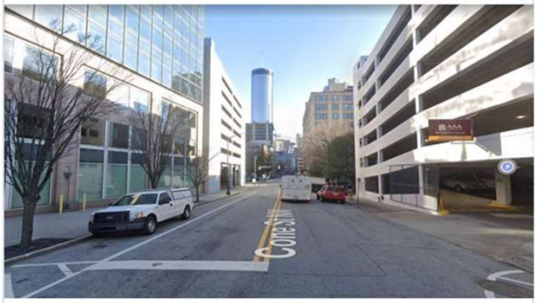
Table 14 – Legend: Top GSI solution vs. roadway modification scenario, 25-year, 24-hour storm

Symbol	Scenario	Solution	# of Segments	Miles
─	1	Bioretention	1382	106.61
─	2	Bioretention	709	53.67
━	3	Bioretention	89	6.12
▬	4	Bioretention	31	1.99
▬	5	Bioretention	11	0.83
─	1	Permeable Pavement	373	27.61
─	1	Subsurface Detention	10	0.79
━	3	Subsurface Detention	8	0.52
─	6	Major Reconfiguration	784	58.30

Approximately half of the remaining roadways require modifications to accommodate at least one type of GSI (roadway modification scenarios 2-5), while the other half require a major reconfiguration (roadway modification scenario 6). The 25-year, 24-hour storm requires reconfiguration of nearly three times as many roadway miles compared to the WQ_v scenario. Of the 58 miles that require a major reconfiguration, 32 (55%) are local, five are collector (9%), and 21 are arterial (36%). The share of arterial segments that require reconfiguration is much higher for this design storm, in part because there are not as many appropriate GSI solutions for arterial roadways, so the range of available storage is limited. Additionally, arterial roadways generally have more drive lanes than other functional classifications because they are intended to move more vehicles. However, an increase in number of lanes translates to wider roadways, which results in large runoff volumes that require a significant amount area for GSI. In other words, the ROW cannot sufficiently store the 100% of the runoff volume generated by a 25-year, 24-hour storm.

Figure 28 reveals continuous stretches of segments that require major reconfiguration along several main arteries running north to south and east to west. In these cases, it may be beneficial to deploy multiple reconfiguration scenarios to evaluate the entire length of the segment to ensure continuity between segments in terms of geometry and GSI design. For major reconfigurations, number of drive lanes will likely be reduced to make room for GSI. Table 15 provides detailed examples of proposed GSI solutions along with the roadway modifications necessary to accommodate each solution for the 25-year, 24-hour scenario.

Table 15 – Example of GSI solutions and roadway modifications, 25-year, 24-hour storm scenario

Detail #	Street Name	Street Type	Existing Conditions	Proposed Solution (WQ_v)
1	St Charles Ave NE	Local	 ROW Width = 70', Roadway Width = 50', Min Clear Zone = 12', Drive Lanes = 2, Parking Lanes = 2	Reconfig. Scenario = 1 - No Change GSI Type = 3 - Permeable Pavement GSI Width per LF of roadway = 14.2' Drive Lanes = 2 Parking Lanes = 2
2	Cone St NW	Local	 ROW Width = 60', Roadway Width = 40', Min Clear Zone = 16', Drive Lanes = 2, Parking Lanes = 2	Reconfig. Scenario = 6 - Major Reconfiguration GSI Type = 1 - Bioretention GSI Width per LF of roadway = 8.0' New Roadway Width = 32'
3	Cherokee Ave SE	Collector	 ROW Width = 60', Roadway Width = 42', Min Clear Zone = 16', Drive Lanes = 2, Parking Lanes = 1, Bike Lanes =1	Reconfig. Scenario = 1 - No Change GSI Type = 3 - Permeable Pavement GSI Width per LF of roadway = 3.4' Drive Lanes = 2 Parking Lanes = 1 Bike Lanes = 1
4	Donald Lee Hollowell Pkwy NW	Arterial	 ROW Width = 60', Roadway Width = 40', Min Clear Zone = 16' , Drive Lanes = 4, Parking Lanes = 0	Reconfig. Scenario = 6 - Major Reconfiguration GSI Type = 1 - Bioretention GSI Width per LF of roadway = 8.0' New Roadway Width = 32'

Reconstructing a corridor provides an opportunity to implement complete street design and improve the roadway for all users, including vehicles, pedestrians, cyclists, and transit operators/riders. Vehicular safety is enhanced by promoting more consistent speeds as well as reducing turning conflicts that result in crashes (FHWA 2021). Pedestrian safety within the crosswalk is increased because the number of lanes to cross are reduced and buffer area is added between the roadway and sidewalk. Figure 29 provides an example of how the city could reduce the number of lanes and make space for dedicated bike lanes. Not only do bike lanes create a dedicated space for cyclists, but they also free up roadway space for permeable pavement application. Alternatively, the "added" space could be re-incorporated into back-of-curb area to accommodate transit stops or wider sidewalks and integrate them with GSI. Incorporating GSI into complete street design can also reduce roadway flooding and improve safety. Furthermore, increased vegetation reduces air and noise pollution (NACTO 2017b). Ultimately, some streets may be better suited for movement of vehicles, but a full reconfiguration of the roadway presents an urban area with the opportunity to reimagine the street grid as a network that incorporates green street practices and serves all users of the roadway.

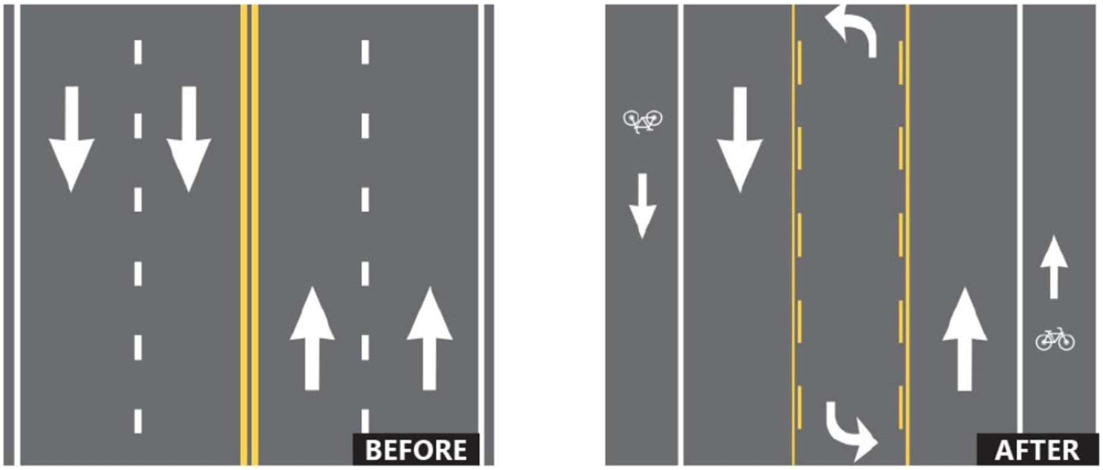
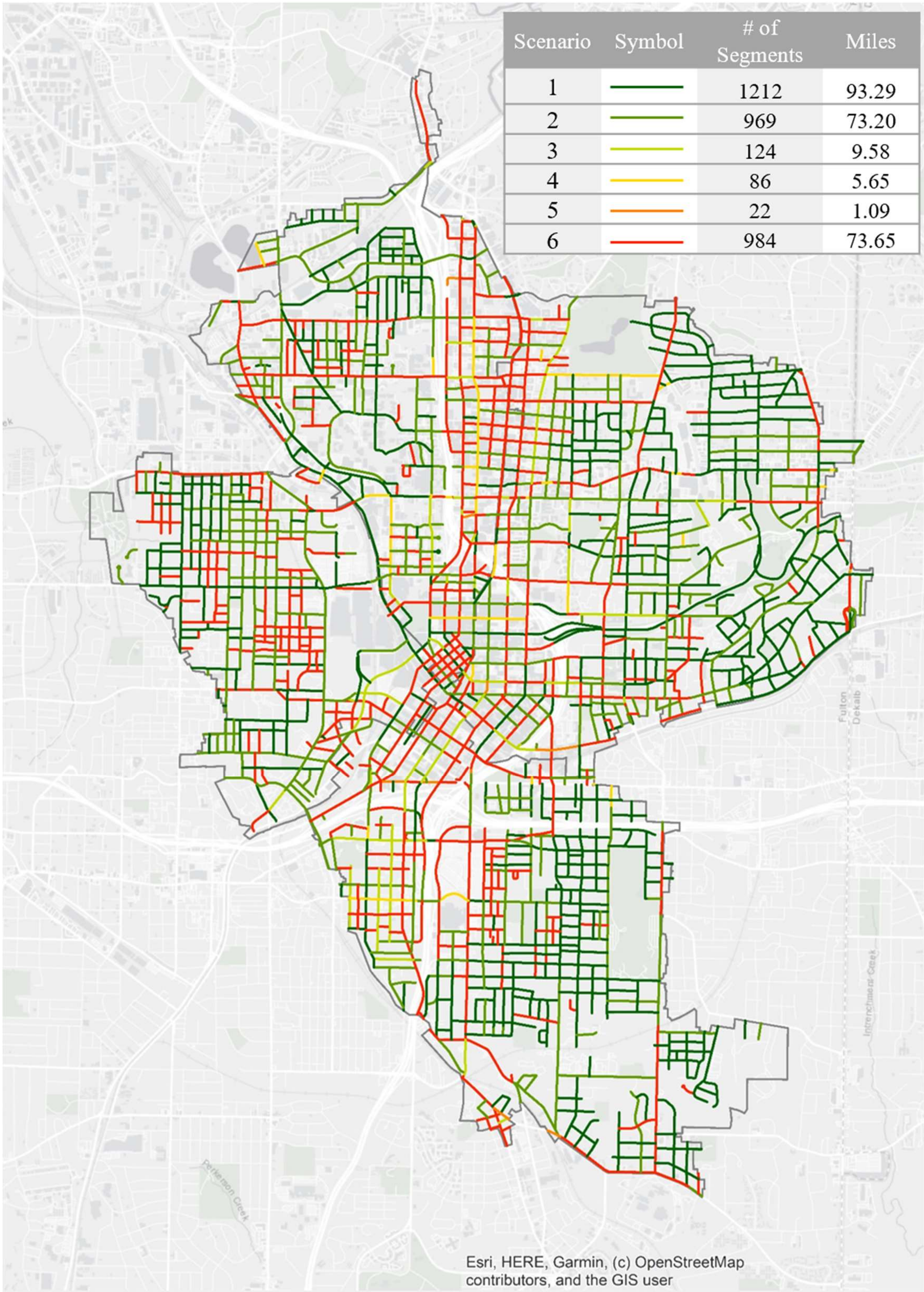


Figure 29 – Roadway reconfiguration scenario
(Source: FHWA, 2021)

Figure 30 shows the minimum roadway modification scenario required to accommodate at least three types of GSI. Approximately 36% of roadways in the analysis do not require any modification to accommodate at least three solutions. Another 32% of roadways only require the reduction of one parking lane, while just under 3% of roadways require the reduction of all on-street parking. Lastly, 29% of roadways require full reconfiguration to accommodate at least three solutions.



Scenario	Symbol	# of Segments	Miles
1	—	1212	93.29
2	—	969	73.20
3	—	124	9.58
4	—	86	5.65
5	—	22	1.09
6	—	984	73.65

Figure 30 – Minimum roadway modification scenario required to accommodate at least three GSI solutions, 25-year, 24-hour storm

4.5.3 100-Year, 24-Hour Storm Results

The top GSI solution and roadway modification combination for each segment in the 100-Year, 24-Hour storm scenario is shown in Figure 31, accompanied by a legend on the following page (Table 14). In this scenario, there are approximately 120 miles of roadway in the study area that do not require any modification to the existing roadway to accommodate at least one type of GSI. Of the 120 miles within the first roadway modification scenario (i.e., no change to the existing roadway), 97 miles propose the top solution, bioretention, 21 miles propose permeable pavement, and 1.3 miles propose subsurface infiltration and detention. Thus, the GSI solutions proposed in the first roadway modification scenario for the 100-year, 24-hour storm account for approximately 47% of all roadway miles in the study area.

Like the 25-year, 24-hour storm scenario, roughly half the solutions proposed require moderate modification to accommodate at least one type of GSI (roadway modification scenarios 2-5) while the other half require a major reconfiguration (roadway modification scenario 6). Although this storm produces significantly more runoff than the 25-year scenario, there is only a slight increase (~7 additional miles) in roadways that require major reconfiguration. However, the GSI solutions proposed for this storm will require a larger share of ROW space. Even so, the relatively minor increase in roadways that require major reconfiguration between storm scenarios provides an argument for reconstructing roadways to treat the 100-year storm rather than the 25-year storm.

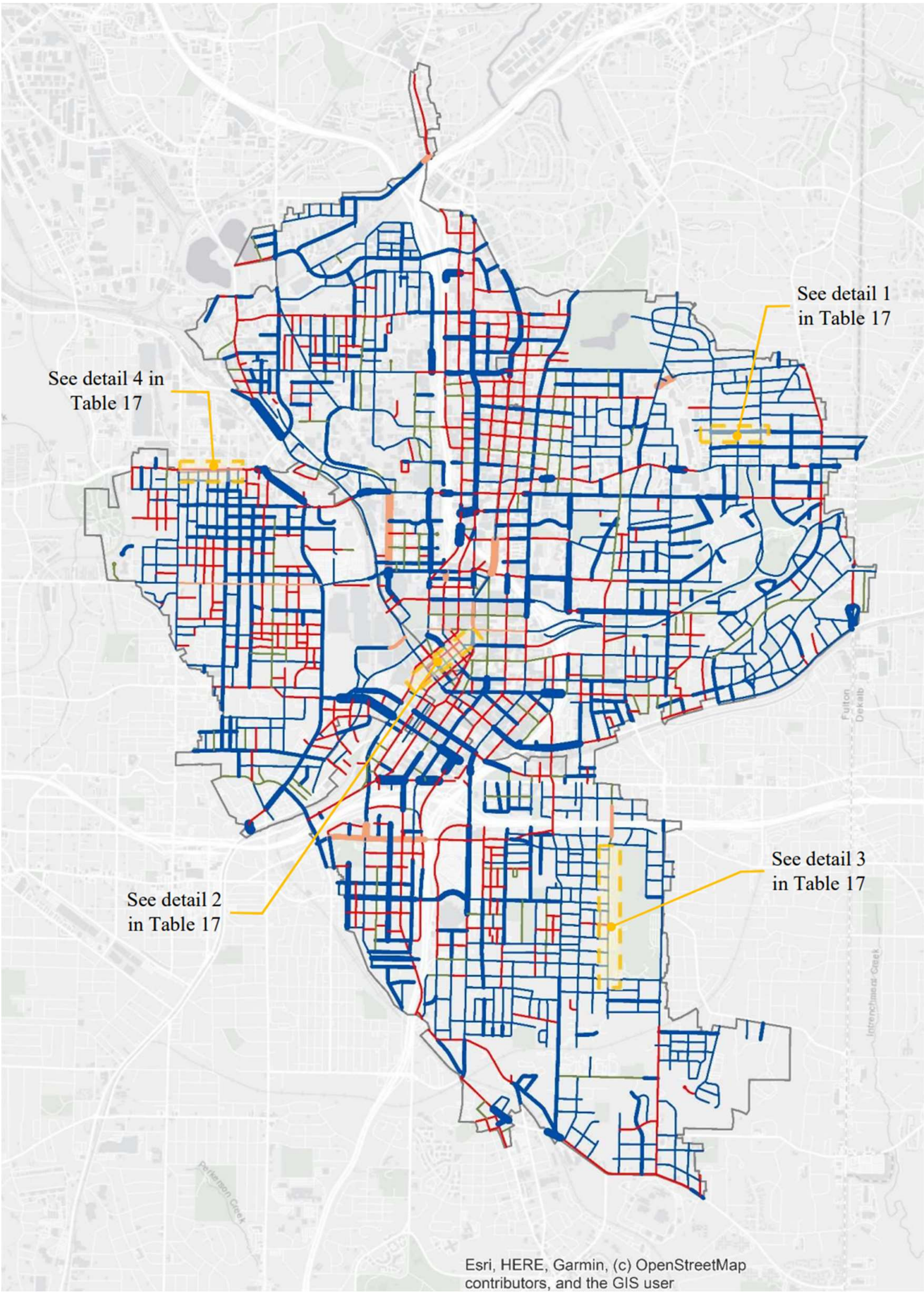


Figure 31 – Top GSI solution vs. roadway modification scenario, 100-year, 24-hour storm

Table 16 – Legend: Top GSI solution vs. roadway modification scenario, 100-year, 24-hour storm

Symbol	Scenario	Solution	# of Segments	Miles
—	1	Bioretention	1258	97.20
—	2	Bioretention	761	57.62
—	3	Bioretention	127	9.62
━	4	Bioretention	31	1.56
━	5	Bioretention	23	1.39
—	1	Permeable Pavement	284	21.16
—	1	Subsurface Detention	18	1.34
—	2	Subsurface Detention	6	0.46
—	3	Subsurface Detention	8	0.64
━	4	Subsurface Detention	11	0.84
—	6	Major Reconfiguration	870	64.62

Figure 32 outlines the roadway segments that require a major reconfiguration. Assuming 10-foot lanes and a minimum sidewalk width of six feet, approximately 20% of roadways require reconstruction to move the curb rather than a reduction in the number of drive lanes. Thirty-six percent (36%) of roadways require a reduction of one lane only, while just under 10% require a reduction of two or more lanes. This analysis assumes that any segments which require a reduction in drive lanes will still require a minimum of two lanes. Therefore, 34% of roadways that require major reconfiguration are “infeasible”, meaning the space available in the ROW cannot adequately support GSI alongside necessary components like vehicular lanes and pedestrian walkways. Each segment should be evaluated on a case-by-case basis for reconfiguration and the ultimate solution to incorporating green streets may prioritize the capture of varying levels of storms from street to street.

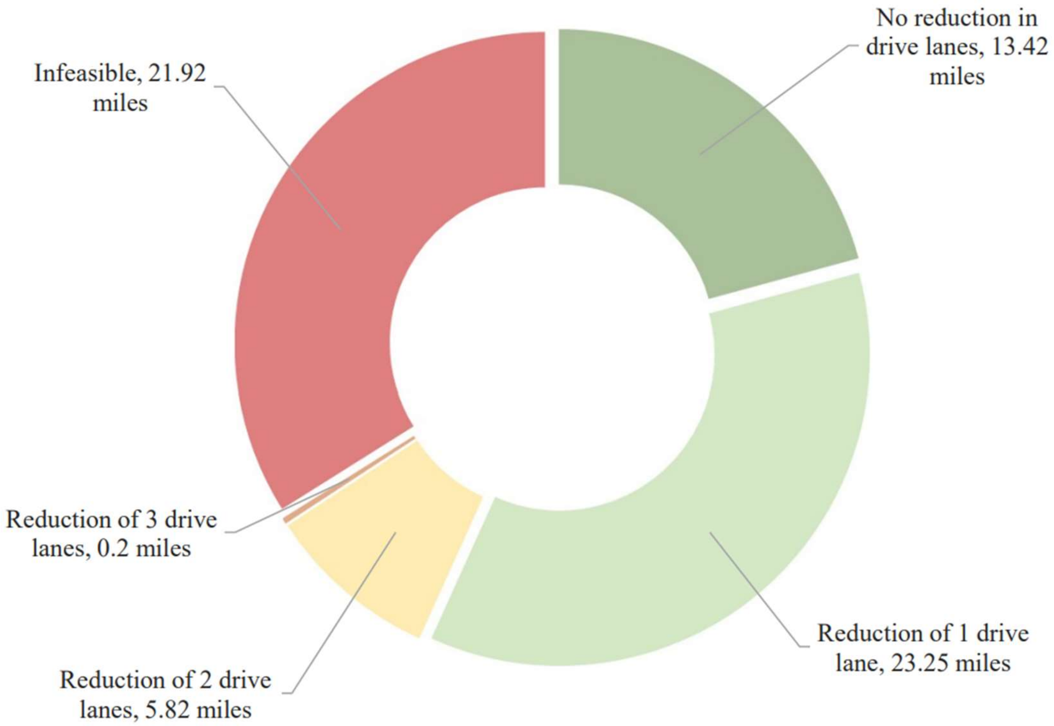


Figure 32 – Required drive lane reductions to accommodate one type of GSI for reconfigured segments

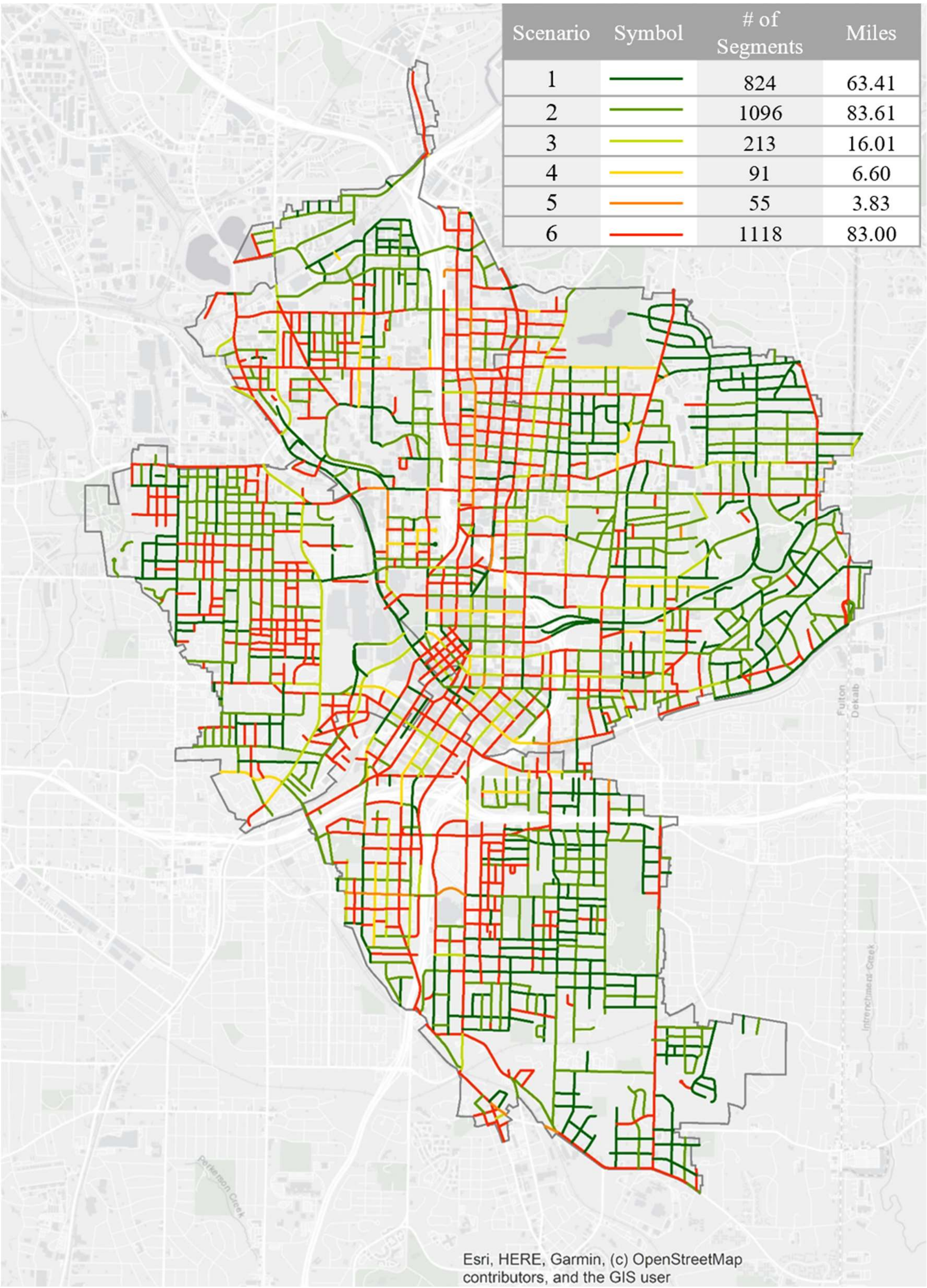
The goal of this analysis is to treat the 100-year storm along every segment using GSI, but the physical and financial feasibility decrease as treatment volume and required GSI area increase. Although planning for the 100-year storm requires considerable resources, almost half of the streets do not require any change to the existing section whatsoever, and only 10% of roadways in the analysis are infeasible. Although capturing the 100-year storm does not physically separate the combined sewer system into two components, statistically speaking, it prevents stormwater from entering the system for 99% of storms each year. While stormwater can still physically enter the system – especially for a storm event more intense the 100-year storm – runoff volumes are significantly reduced along with CSO events (Atlanta Regional Commission 2016). Additional benefits include mitigation of urban heat island effect, reduced energy demand due to lower ambient air temperature, and lower probability of drinking water impairment (Atlanta Regional Commission 2016). Table 17 provides detailed examples of proposed GSI solutions along with the roadway modifications necessary to accommodate each solution for the100-year, 24-hour scenario.

Table 17 – Example of GSI solutions and roadway modifications, 100-year, 24-hour storm scenario

Detail #	Street Name	Street Type	Existing Conditions	Proposed Solution (WQ_v)
1	St Charles Ave NE	Local	 ROW Width = 70', Roadway Width = 50', Min Clear Zone = 12', Drive Lanes = 2, Parking Lanes = 2	Reconfig. Scenario = 2 - Reduce 1 parking lane GSI Type = 1 - Bioretention GSI Width per LF of roadway = 12.3' Drive Lanes = 2 Parking Lanes = 1
2	Cone St NW	Local	 ROW Width = 60', Roadway Width = 40', Min Clear Zone = 16', Drive Lanes = 2, Parking Lanes = 2	Reconfig. Scenario = 6 - Major Reconfiguration GSI Type = 1 - Bioretention GSI Width per LF of roadway = 9.8' New Roadway Width = 30'
3	Cherokee Ave SE	Collector	 ROW Width = 60', Roadway Width = 42', Min Clear Zone = 16', Drive Lanes = 2, Parking Lanes = 1, Bike Lanes =1	Reconfig. Scenario = 1 - No Change GSI Type = 3 - Permeable Pavement GSI Width per LF of roadway = 14.7' Drive Lanes = 2 Parking Lanes = 1 Bike Lanes = 1
4	Donald Lee Hollowell Pkwy NW	Arterial	 ROW Width = 60', Roadway Width = 40', Min Clear Zone = 16’ , Drive Lanes = 4, Parking Lanes = 0	Reconfig. Scenario = 6 - Major Reconfiguration GSI Type = 1 - Bioretention GSI Width per LF of roadway = 9.8’ New Roadway Width = 30’

Figure 33 shows the first instance in which a roadway modification scenario can support at least three types of GSI for the 100-year, 24-hour storm scenario. Twenty-five percent (25%) of the roadways within the analysis do not require modification to accommodate at least three solutions. Approximately 39% of roadways require reduction of one parking lane, and 4% of roadways require elimination of all on-street parking. The remaining 32% of roadways (in terms of miles) require a major reconfiguration to accommodate three solutions, a 10% increase from the previous storm scenario.

As expected, accommodating at least three types of GSI for the 100-year, 24-hour storm requires significant roadway modifications for a large share of segments. Many segments within Atlanta's downtown and midtown areas would need to be reconfigured to accommodate this design storm to support multiple GSI types. Like the previous two scenarios, local streets within residential neighborhoods require little to no modification to support multiple GSI options sized for the 100-year storm.



Scenario	Symbol	# of Segments	Miles
1	—	824	63.41
2	—	1096	83.61
3	—	213	16.01
4	—	91	6.60
5	—	55	3.83
6	—	1118	83.00

Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user

Figure 33 – Top GSI solution vs. roadway modification scenario, 100-year, 24-hour storm

4.6 Discussion

4.6.1 Result Accuracy

Assumptions throughout this analysis, such as 100% pavement coverage and short times of concentration, were intended to produce conservative estimates for runoff volumes generated by each storm. However, several unknown factors may contribute to a higher (or lower) runoff volume than what was calculated. First, the runoff calculations only consider the stormwater generated within the roadway rather than the entirety of the ROW due to a lack of data regarding adjacent land use, such as sidewalks, landscape buffers, and other existing features within each segment. Therefore, if excess pavement or other hardscaped areas exist adjacent to the roadway, but still within the ROW (e.g., public sidewalks), the contributing area and subsequent runoff volumes will be larger than what was calculated. In such cases, the GSI proposed would require a larger footprint than what is calculated in this analysis. However, the analysis is still somewhat conservative because the roadway is the largest source of runoff in the ROW section, and consists only of pavement, which translates to the maximum amount of runoff possible for the roadway area.

A comprehensive existing conditions analysis may also impact the results of this analysis. For example, if the ROW width is not accurate, there may be more (or less) area available for GSI than what was assumed. Larger ROW widths translate to a less disruptive roadway modification scenario and increase physical feasibility. On the contrary, there may be an abundant number of shallow utilities that limit the overall depth of the GSI, negatively impacting the assumed storage (CF/SF of GSI). In those cases, the required area for GSI will increase and the roadway modification scenario will become more intense, i.e., require the reduction of all parking lanes rather than just one. Topography will also impact the assumed storage of GSI. Steep slopes make it hard for GSI to achieve its specified ponding depth and can also lead to turbulent runoff conditions that destroy vegetation. GSI placed in challenging topographical areas will require specialized construction methods, robust vegetation, and frequent maintenance. The City of Atlanta contains several roadways with steep longitudinal slopes, which will impact GSI storage efficiency and design.

The Green Street Toolkit serves as an effective planning tool and is the first step toward implementation of green infrastructure on a large-scale, but proper due diligence regarding site characteristics must be performed to combat any storage limits or design challenges such as topography or utility conflicts.

4.6.2 Design Implications

The Green Street Toolkit presented in this research focuses on the physical feasibility of GSI in the ROW. However, the roadway modifications proposed may lead to push-back from public or private stakeholders. First off, five out of six roadway modification scenarios reduce on-street parking, which requires buy-in from local stakeholders, especially when alternative modes of transportation are limited. Although removal of on-street parking is a controversial subject in the City of Atlanta (and beyond), there has been a recent push by city planning officials to reduce on-street parking and eliminate parking minimums dictated by zoning and building-type. However, push-back from other city departments and adjacent property owners can result in project delays and negatively impact the GSI design and approval process.

A reduction in sidewalk widths may negatively impact an area's walkability. Information regarding adjacent land use and pedestrian activity should be retrieved during the existing conditions assessment to ensure adequate pedestrian access is maintained wherever GSI is installed. In many cases, GSI has the potential to enhance pedestrian safety by improving visibility at intersections and decreasing vehicular speeds. Finally, the utilization of vegetation in lieu of pavement creates a welcoming atmosphere, so GSI should be seen as an improvement, rather than a hindrance to, the pedestrian environment.

Although neighborhood boundaries were incorporated into the base dataset, they did not impact GSI solutions or roadway modifications. Ideally, the inclusion of neighborhood boundaries promotes long-term, neighborhood level planning in the next steps of the green street design process. Neighborhood context may alter final GSI selection or the selection's individual characteristics, like plant selection, curbing, or drainage grates. Since the Green Street Toolkit is intended to follow an incremental process, design continuity among adjacent segments will be challenging. Adhering to a long-term plan within neighborhoods will promote consistent design, facilitate the development of maintenance scheduling, and inform design improvements over the 40-year reconstruction period.

4.6.3 Combined Sewer Separation

The ultimate question within this research is whether a programmatic green streets approach is capable of removing stormwater generated in the roadway (and ideally, the entire ROW) from the combined sewer system. To address this, runoff generated by the 100-year, 24-hour storm was quantified within the roadways that coincide with Atlanta's

CSA and GSI was sized to capture the resulting volume. The results show the runoff from a 100-year, 24-hour storm can be captured using only GSI for 90% of roadways in the CSA, but roadway modifications must be made on 137 miles (53%) of segments. Beyond a reduction of parking lanes and sidewalk widths, major roadway reconfigurations require a decrease in drive lanes for 74 miles (29%) of roadways in the study area. Although data regarding public and franchise utilities was not collected, utility removal and relocation will be required for most, if not all, GSI projects, which could extend the project completion timeline and increase construction cost. Though a green streets approach is physically possible in most cases, financial implications can further impact feasibility. Moreover, treating a storm of this magnitude requires major reconfiguration and reconstruction at a roadway corridor level, rather than incremental changes to individual segments, a severe departure from the methodology the Green Street Toolkit proposes.

In addition to feasibility and budgetary issues, designing for the 100-year, 24-hour storm does not address the most intense storms, despite its common usage as the most extreme storm scenario in stormwater drainage design. For example, in 2009, Austell, Georgia, a town located 17 miles east of Atlanta, experienced a storm that exceeded the 500-year (0.2%) storm event in some drainage basins (USGS 2010). Therefore, designing for the 100-year storm event may not adequately address runoff generated by extreme storm events, even if the probability of such an occurrence is relatively low. Although it is outside the scope of this research, climate change has triggered a critical review of whether current stormwater design criteria is adequate at addressing urban flooding issues likely to occur in the near future (Markolf et al. 2021).

Rather than a blanket requirement, GSI and the Green Street Toolkit should be utilized for capturing a mixture of storm durations and intensity, ranging from the 25-year, 24-hour storm to the 100-year, 24-hour storm, depending on existing conditions. To mimic a comprehensive sewer system, connecting completed GSI projects may be beneficial, either through traditional sewer pipes or other low impact SCMs, such as swales. Connecting GSI would allow areas with excess runoff to make use of underutilized GSI nearby. Alternatively, GSI could be routed to larger SCMs, such as retention ponds, or released to local bodies of water. GSI enables runoff to receive significant treatment through infiltration, then released into local bodies of water without the harmful public health implications brought on by a CSO event.

Simply designing GSI to capture the runoff from a design storm does not inherently produce physical separation from the combined sewer system. Instead, the runoff generated in the ROW no longer relies upon the underlying sewer system for all storm intensities of a 24-hour duration *up to* the design storm event – ideally the 100-year storm. Unless major flood controls are in place, intermittent connections to the combined sewer should be maintained to provide a safeguard for extreme events. These connections would be used sparingly and the supplementary GSI system would still eliminate the main issues associated with CSO events, such as limited sewer capacity, back-ups, and local flooding.

4.6.4 Future Work

There are several pathways to expand upon this research. First, enhanced data collection on existing conditions could yield more accurate results throughout the analysis. A profile of physical characteristics within the ROW, including complete information regarding existing roadway widths, sidewalk widths, and buffer space would fine-tune the analysis and provide more accurate data for future design phases. Existing lane width and topography would also aid in determining overall feasibility for GSI in the ROW. Likewise, details regarding additional roadway components such as shoulders or medians should be documented because they are prime locations for GSI. Lastly, a comprehensive parking inventory for both on-street and off-street parking would allow designers to make informed decisions regarding the impacts of removing on-street parking.

In addition to enhanced data collection for the existing conditions analysis, detailed information regarding impacts from storms, such as flooding complaints or reports of damaged infrastructure or property would help guide phasing of a green streets program by addressing the needs of more heavily impacted areas first. Ideally, this data could be incorporated into a GIS model and overlayed with the existing conditions analysis to view both sets of data in tandem.

Lastly, securing a comprehensive inventory of all past green infrastructure projects across Atlanta would create a blueprint for documenting future green street projects. Details such as plant lists, recommended design storms, and site challenges would provide priceless firsthand knowledge for future projects. Just as engineers and architects are required to submit “as-built” drawings for current land-development projects, detailed information should be submitted for all green infrastructure projects as well. While the City of Atlanta does provide an overview of green infrastructure projects on their GIS website, it should be supplemented with the abovementioned technical information to educate designers, engineers, and contractors, and inform future projects.

CHAPTER 5. POLICY RECOMMENDATIONS

The Green Street Toolkit analysis demonstrates that The City of Atlanta would benefit from the implementation of a green streets program within The City's proposed linear construction policy. At a minimum, any roadway that is reconstructed should be required to capture and store runoff generated by the WQ_v design storm using GSI. This work supports an even stricter policy by uncovering that almost half of the roadways within the CSA have adequate space to implement GSI to capture the 100-year, 24-hour storm without any significant changes to the roadway. While site conditions will ultimately dictate the design storm that can be treated with GSI, the Green Street Toolkit can be used to initially determine design options for a roadway reconstruction project. Therefore, it is recommended that the City of Atlanta consider developing GSI requirements for roadways based on the Green Street Toolkit and enforce such requirements within their linear construction policy. The following sections outline recommendations the City should consider before establishing a formal policy.

5.1 Administrative Framework

Green street policies in US cities, such as Seattle or Portland, provide a precedent for how the City of Atlanta might implement a successful linear construction policy. In the case of Portland, whose programmatic green streets policy was introduced in 2007, planning, implementation, and maintenance of green streets was a cross-bureau effort (i.e., The Green Streets Cross-Bureau Team) that included members from planning, development, maintenance, environmental, parks and recreation, and transportation departments (City of Portland 2007). The team established a green streets policy to achieve shared goals between departments, triggering wide-spread acceptance and support for green street practices within the local government. In the City of Atlanta, multiple departments manage GSI within the, but exact responsibilities of each department are unclear, leaving gaps in the design, construction, and maintenance processes. The City of Atlanta must establish a coalition of stakeholders from all relevant departments to address GSI for green streets. Routine meetings would establish rapport between departments and help identify commonalities to pursue in a formal green streets program. While the City of Atlanta does have a multidisciplinary team that focuses on GSI (i.e., The Green Infrastructure Task Force), their main goal is to enforce the requirements of Atlanta's stormwater ordinance on private property, rather than the public ROW (City of Atlanta DWM 2018). Furthermore, the Task Force does not consist of major stakeholders that would need to be included in a green streets program, such as The Atlanta Department of Transportation or GDOT. Therefore, a separate team should be compiled of all relevant stakeholders to focus solely on the implementation and management of a green streets program within the larger linear construction policy.

5.2 Project Tools

After establishing an administrated framework and compiling a GSI green street team, there are several tools that the City should publicize prior to the issuance of a formal policy. For example, Portland's policy is comprehensive in that it addresses short and long-term planning for projects, technical guidance and specifications, and maintenance protocols. Likewise, SPU manages Seattle's natural drainage program and has issued six volumes of green infrastructure manuals that cover project initiation, options analysis, design, construction, operations and maintenance, and monitoring (NACTO 2016). Both cities have had long-running green streets programs recognized as best practices throughout the US and a blueprint for other cities, due in part to the abundant resources and support they offer. To follow in these cities' footsteps, the City of Atlanta must expand upon the GSI guidance offered in the Green Street Toolkit to provide adequate technical support for all phases of a project. The Green Street Toolkit provides a starting point for project initiation, options analysis, and design, but the Toolkit does not offer guidance for funding, construction methods, operations, or maintenance.

5.2.1 Construction Standards

The construction of GSI is constantly evolving, so there is a lack of concrete documentation of design details, standards, and specifications. GSI is not a one-size-fits-all type of infrastructure, which has hindered the formal issuance of specific construction standards. In Portland's green streets program, thorough documentation of completed projects has led to the creation of a Green Streets Notebook that provides design details and guidance for every type of GSI used within their program (City of Portland 2007). At first, the notebook's standards were flexible, but as the city learned from its mistakes, the notebook evolved into a formal manual. Eventually, the Green Streets Notebook was able to provide guidance for site-specific challenges and reduce costs on future projects (City of Portland 2007). Standards and specifications for GSI construction cannot be created overnight, but they do require a starting point. While the City of Atlanta and The Atlanta Regional Commission have some GSI details available on their websites, a set of construction standards specific to green streets needs to be created before a linear construction policy can be issued. Ideally, a cross-bureau team can develop standards that meet the criteria that the City of Atlanta requires for both stormwater and roadway infrastructure. Like Portland's Green Streets Notebook, standards and details should start with some flexibility, then updated routinely as projects are completed.

5.2.2 Monitoring and Maintenance

Establishing maintenance protocols for GSI is equally as important as developing construction standards. Unlike conventional sewer infrastructure, which generally performs as designed, GSI requires monitoring and maintenance to ensure proper functionality and performance (i.e., capturing and treating the intended design storm). Philadelphia's Green City, Clean Waters program adheres to a comprehensive monitoring plan that not only monitors GSI, but also the combined sewer system and receiving waters. The Philadelphia Water Department is responsible for monitoring GSI and collecting data specific to each type of GSI's function, including inflow, surface infiltration, storage, subsurface infiltration, soil moisture, and bypass flow (Cammarata 2014). These measurements are then compared to the design parameters to determine the effectiveness of GSI and make critical improvements to the existing infrastructure.

Routine monitoring of GSI is also vital for maintenance scheduling and methods. If GSI is functioning properly, but a series of storm events causes a sudden increase in bypass flow, maintenance may be required. The Atlanta Regional Commission and the GSMM both provide recommended maintenance schedules for all types of GSI proposed in The Green Street Toolkit, but like construction standards, they merely offer a starting point since every type of GSI possesses unique design attributes and site conditions. Furthermore, the maintenance schedules offer little in the way of post-construction monitoring, a fundamental component of determining maintenance needs. Maintenance schedules and activities depend on several factors, including site conditions (topography, amount of traffic, type of runoff, etc.) and meteorological conditions (frequent storms and dry periods). While routine monitoring and maintenance are important throughout the lifetime of GSI, they are especially crucial in the early years of a green streets program because they eventually establish a precedent for future projects.

5.3 Pilot Program

A pilot program is a common denominator that successful green street programs in other cities often share. Pilot programs address gaps in planning, construction, and maintenance of green street projects before they are implemented at a larger scale. Although Atlanta has deployed GSI in the roadway for several past projects, the planning, design, and implementation processes were inconsistent from one project to another. Therefore, The City of Atlanta should start a pilot program to test out the Green Street Toolkit methodology, construction methods, and maintenance protocols before finalizing a linear construction policy. The pilot program should include a variation of green street projects with different GSI types, roadway classifications, and site conditions. Once a project has been completed, thorough documentation of project challenges and GSI design should be provided by the project team. In Portland, documentation of pilot projects has catalyzed the formulation of a Green Streets Notebook, which served as a foundation for formal GSI standards and specifications, and enabled design innovation and cost savings (City of Portland 2007).

Every one of the policy recommendations outlined in this chapter could be addressed with a pilot Program. The program would also provide an opportunity to secure buy-in from City of Atlanta stakeholders before a formal policy is put into action. Pilot projects offer a tangible example of green streets for the public and serve as an educational tool that exemplifies the benefits of GSI.

CHAPTER 6. CONCLUSION

Increased land development across US urban areas has generated an onslaught of issues that have forced cities to rethink the way they plan and design stormwater infrastructure. It is estimated that 60% (or more) of land in urban areas is made up of impervious surfaces, about half of which are roadways (NACTO 2017a). Traditionally, roadways have utilized the underlying sewer system to quickly capture and eliminate runoff generated by a storm. Ceaseless land development and increasing storm intensity and frequency have rendered the existing sewer system inadequate, leading to overflows and local flooding. Capacity issues are especially prevalent in urban cores where street grids are well-established and pavement is ubiquitous. These areas are often served by aging combined sewer systems that were originally designed to convey significantly less runoff volume than what today's urban conditions warrant.

Historically, the approach to increase capacity has been to separate the combined sewer system into two parts: sanitary and stormwater. However, retrofitting the combined system in densely developed urban areas oftentimes constitutes a monumental effort that can be plagued by economic and physical challenges. Therefore, many cities have invested in large-scale gray infrastructure, such as CSOs and storage tanks, which have proven to be short-sighted solutions, unable to keep up with the increasing capacity needs of growing cities. From 2001 to 2017, the City of Atlanta spent $1.07B on capacity relief projects, and while additional projects are nearing completion or in the pipeline, overflows and backups persist (City of Atlanta 2014). Moreover, there are 11 square miles within the core of the city that are served by the combined sewer system, yet no further plans to separate these segments currently exist (City of Atlanta 2014).

Sewer separation and large-scale capacity relief projects are not the only solutions for stormwater mitigation in combined sewer areas. Green infrastructure has proven to be a viable alternative for conventional sewer systems because functions like traditional infrastructure while providing ancillary benefits. Portland and Seattle are prime examples of cities turning to an emerging subset of civil engineering known as green infrastructure to address CSO-related issues. Both cities have recognized the value of utilizing green infrastructure for roadside applications (i.e., green streets), since paved surfaces are one of the largest contributors of increased runoff. Portland began installing green street components in 1998 and the city's system has grown to include more than 2,520 features as of 2020 (City of Portland 2022b). Approximately 200 million gallons of stormwater are captured by these facilities annually, most of which are removed from the combined portion of the sewer system (City of Portland 2022a). The green street system, along with other SCMs like green roofs and rain harvesting systems, manage approximately 51% of all stormwater from city-owned impervious surfaces (City of Portland 2022b). In addition to stormwater mitigation, Portland cites various positive externalities stemming from its green streets program, including enhancements to the pedestrian environment, reduced air temperature, and additional habitat for wildlife (City Parks Alliance 2022). Both Portland and Seattle were early adopters of green streets and their long-running programs have continued to gain momentum due to the immense number of benefits GSI has provided – at a fraction of the cost of conventional infrastructure. Although both cities still have work to do, they are well on their way to permanently eliminating CSO events. This begs the question: What can green streets do for other cities?

This work presents a methodology for the implementation of green streets within urban areas that are currently served by combined sewer systems. The methodology is intended to be utilized in the first phase of the planning and design process and applied to an existing roadway that is near the end of its design life and due for reconstruction. The intent of this work is to provide a contribution that bridges the gap between policy and implementation. On the policy side, the methodology is intended to inform the standard that should be enforced (i.e., should a green street policy require capturing the first 1.2” of runoff, the 25-year, 24-hour storm, the 100-year, 24-hour storm, or something else entirely?). On the implementation side, the methodology provides a standardized prescription for green street design that can be applied universally (i.e., the type of GSI that should be considered on a given roadway segment and the subsequent impact to the geometric characteristics of the roadway).

The methodology proposes six types of GSI for green street applications: bioretention, bioswales, stormwater planters, infiltration trenches, subsurface infiltration and detention, and permeable pavement. The optimal GSI solution for each segment is determined using factors such as functional roadway classification, GSI preference (per Section 3.4.2), required GSI area, and available space for GSI along the segment. The top solution for a given segment also incorporates the extent of roadway modifications that must be made to accommodate proposed GSI.

The City of Atlanta is the focus of the methodology and analysis using three storm scenarios. The first storm scenario uses the water quality volume (WV), which is equivalent to the runoff generated by the first 1.2” of rainfall that falls on a site. The wa_{ve} storm scenario represents the threshold for stormwater requirements set forth by the State of Georgia for new development and these requirements are stricter than Atlanta’s local green infrastructure ordinance. In this storm scenario, 55% of roadways in Atlanta’s CSA can accommodate multiple types of GSI without major roadway modifications. An additional 34% of roadways can accommodate multiple designs with some modifications, while the remaining 11% require a complete reconfiguration. Therefore, it is acceptable to assume that green streets can effectively capture, treat, and store runoff generated from the WQ_v storm scenario.

The second scenario presented is the 25-year, 24-hour storm, which is a common design storm benchmark for stormwater control measures across the US. Approximately 53% of roadways can accommodate at least one GSI solution without modifications to the existing roadway configuration and 36% can accommodate at least three GSI solutions without modification. Expanding the solution to accommodate three types of GSI permits greater flexibility in the design process and allows input from stakeholders to determine which type of GSI most appropriately suits each segment’s character. Utilizing multiple types of GSI along one segment may help alleviate design challenges encountered on complicated sites or provide aesthetic benefits. Approximately 29% of roadways will require a complete reconfiguration to accommodate at least three solutions, but that share decreases to 23% if only one solution needs to be accommodated. The 25-year, 24-hour storm scenario requires a larger variety of roadway modifications to accommodate GSI than the WQ_v scenario. The variation in roadway modifications is expected because a greater volume of runoff must be captured in the 25-year, 24-hour storm scenario. Green streets still provide an effective mechanism for controlling runoff generated by the 25-year, 24-hour storm for over 50% of segments, but may not provide a universal solution across the CSA for a design storm of this magnitude.

The 100-year, 24-hour storm analysis is intended to represent the effectiveness of green streets in an intense, infrequent runoff scenario that likely produces a CSO event. Successfully capturing the runoff generated in the ROW for a storm of this intensity would greatly reduce dependence on the underlying combined sewer system. Furthermore, green streets decrease the probability of a CSO event since a significant portion of stormwater runoff is captured using GSI. Any ROW-generated runoff that does eventually reach the combined sewer system, does so at a much slower rate due to the increase in pervious surfaces, freeing up system capacity for runoff generated elsewhere. Approximately 47% of roadways (in terms of mileage) can accommodate at least one GSI solution without any modifications to the existing roadway section, while 28% require some modifications, and 25% require a major reconfiguration. If three GSI solutions must be accommodated on any given segment, 25% of roadways do not require any modification to the existing configuration, 43% require some modifications, and 32% require a major reconfiguration. In this scenario, the share of segments that require modifications to the existing configuration are significant, regardless of whether one or three GSI solutions must be accommodated. Therefore, green streets do not offer a comprehensive solution for eliminating combined sewer dependency across the entirety of the CSA. However, the streets that can accommodate one or three solutions, while requiring minimal modifications, are candidates for further study. While green streets may not be a silver bullet, this work demonstrates that green streets are an effective strategy for stormwater relief for nearly half of the roadways in Atlanta’s CSA.

The results presented provide a strong foundation for the implementation of a green street design process, but further research must be completed prior to the issuance of a formal program and policy. A robust existing conditions inventory will yield more accurate results for factors included in the analysis, such as ROW space available for GSI and required roadway modifications. Further development of standard details and specifications will ensure compliance with applicable regulations at local and state levels. Creating a level of standardization for the GSI proposed in this work will also contribute to the establishment of operations and maintenance protocols. Establishing standards for construction and operations will impact data inputs in the analysis, such as available GSI storage and implementation preference, which could alter the results. While the optimal GSI solution and associated roadway modification for an individual segment may change with a greater level of detail, the methodology will not.

The Green Street Toolkit presented in this research provides a framework for a green streets policy and a foundation for future analysis. Green streets provide an opportunity for cities to transform their liabilities into environmental assets. Furthermore, they allow for a flexible design and implementation process that requires very little upfront investment. Successful green street programs across the US have rendered more resilient cities that are prepared to combat combined sewer issues and adapt to changing climactic conditions. It’s time for other cities to stop paving paradise to put up a parking lot, and instead, put up a green street.

APPENDIX A. GREEN INFRASTRUCTURE DETAILS AND ASSUMPTIONS

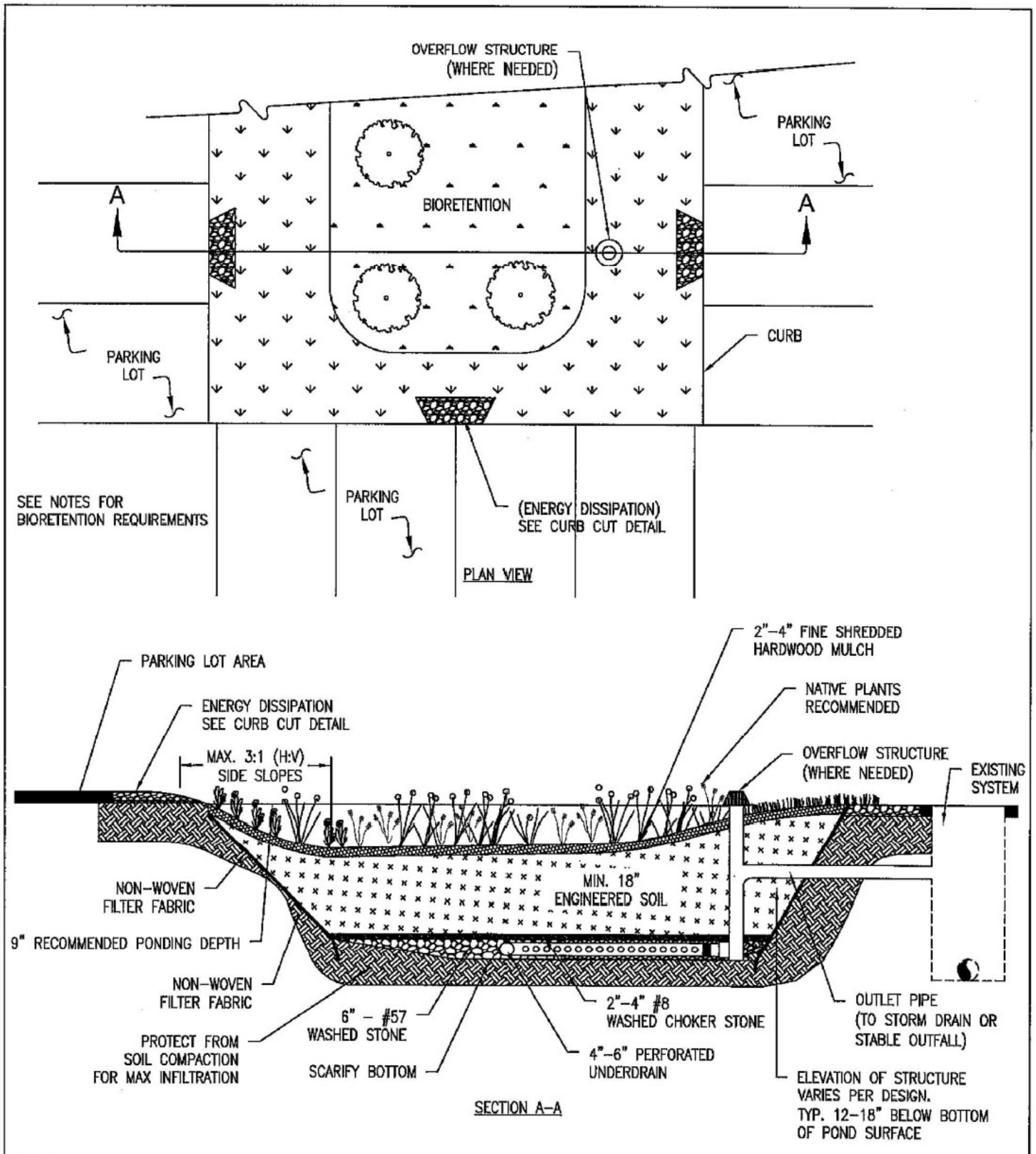
Bioretention

Design Assumptions	
Length (ft)	10.0
Width (ft)	10.0
Area (SF)	100.0
Bioretention Media Depth (in)	36.0
Gravel Depth (in)	6.0
Mulch Depth (in)	3.0
Ponding Depth (in)	9.0
Total Depth (ft)	4.0

		Unit Prices					
Item / Activity	**Unit**	**2005 Low Estimate**	**2005 High Estimate**	**2005 Average**	**2021 Average**	**QTY**	**Item / Activity Cost**
Excavation	CY	$8.00	$10.00	$9.00	$12.92	16.7	$215.25
Geotextile fabric	SY	$1.00	$5.00	$3.00	$4.31	31.1	$133.93
Underdrain (perforated pipe 4" dia.)	LF	$8.00	$15.00	$11.50	$16.50	10.0	$165.03
Gravel	CY	$30.00	$35.00	$32.50	$46.64	1.9	$86.37
Bioretention media	CY	$40.00	$60.00	$50.00	$71.75	11.1	$797.22
Mulch	CY	$30.00	$35.00	$32.50	$46.64	0.9	$43.18
Plants	Ea	$5.00	$20.00	$12.50	$17.94	67.0	$1,201.81
						Total Cost	$2,642.79
						Cost PSF	**$26.43**

Storage Type	**Depth (in)**	**Void Ratio**	**Storage (CF)**
Surface (Ponding)	9.0	-	75.0
Soil	36.0	0.32	80.0
		Total Storage	155.0
		Storage PSF	**1.71**

Calculation Notes:
1. 2005 High and Low Estimates retrieved from: *Low Impact Development for Big Box Retailers, EPA 2005*
2. A CPI inflation factor of 1.435 was used to convert 2005 dollars to 2021 dollars (*https://www.bls.gov/data/inflation_calculator.htm*)
3. Excavation quantity calculated based on area x total depth
4. Filter fabric quantity calculated based on placement along bottom and perimeter of excavation
5. Plants placed every 1.5' on center
6. Void Ratio retrieved from COA Small Commercial Green Infrastructure Manual
7. Soil Infiltration Rate Assumed to be 0.25 in/hr



NOTE:
DESIGNER TO SHOW DETAIL OF PIPE CONNECTIONS TO PROPOSED/EXISTING STORM SYSTEM.

N.T.S.

SMALL COMMERCIAL GUIDE TYPICAL DETAILS

BIORETENTION

NOTES:

1. APPROPRIATE PLANTS AND PLANTING SCHEDULE SHALL BE PROVIDED.
    a. WOODY VEGETATION SHOULD NOT BE PLANTED WITHIN TWO FEET OF INFLOW OR OUTFLOW STRUCTURES.
2. APPROPRIATE MULCH LAYER SHALL BE PROVIDED (2–4" OF FINE SHREDDED HARDWOOD)
3. ENGINEERED SOIL MIX AT LEAST 18" DEEP. ALTERNATE ENGINEERED SOIL MIXES WILL BE CONSIDERED WITH APPROPRIATE TEST AND DOCUMENTATION. GREATER DEPTH OF ENGINEERED SOIL MAY BE NEEDED DEPENDING ON PLANT TYPE AND SPECIFICATIONS.
4. GRAVEL AND PERFORATED PIPE UNDERDRAIN SYSTEM
    a. GRAVEL: 6" LAYER ASTM D448 SIZE NO.57 WASHED STONE AND SHOULD BE SEPARATED BY A THIN 2 TO 4 INCH LAYER OF CHOKER STONE (ASTM D 448 SIZE NO. 8, 3/8" TO 1/8" OR ASTM D 448 SIZE NO. 89. 3/8" TO 1/16")
    b. PERFORATED PIPE: 4 TO 6" PERFORATED PVC (AASHTO M 252), 3/8" PERFORATION SPACED 6' ON CENTER. NO SOCK PIPES SHALL BE PERMITTED.
    c. NON–WOVEN SEPARATION GEOTEXTILE MAY BE UTILIZED ON THE SIDE SURFACE INTERFACES ONLY
5. INSTALLATION SHOULD OCCUR AFTER THE CONTRIBUTING DRAINAGE AREAS TO THE BIORETENTION AREA HAVE BEEN STABILIZED. IF THIS IS NOT FEASIBLE, STORMWATER FLOW SHALL BE DIVERTED AROUND THE BIORETENTION AREA. PROTECT AREA WITH TEMPORARY EROSION AND SEDIMENT CONTROL MEASURES. IF SEDIMENT ACCUMULATES IT MUST BE REMOVED.
6. INSTALLATION OF ENGINEERED SOILS MUST BE COMPLETED IN A MANNER THAT WILL ENSURE PRESERVATION OF THE INFILTRATIVE CAPACITY OF THE UNDERLYING SOILS. THE MOISTURE CONTENT OF THE SOIL SHALL BE LOW ENOUGH TO PREVENT CLUMPING AND COMPACTION DURING PLACEMENT.
7. TO PREVENT COMPACTION WITHIN THE LIMITS OF THE BASINS, ONLY HAND LABORERS, SMALL EXCAVATION HOES WITH WIDE TRACKS, LIGHT EQUIPMENT WITH TURF TIES, MARSH EQUIPMENT OR WIDE–TRACK LOADERS MAY BE USED. NO HEAVY EQUIPMENT SHALL BE USED WITHIN THE PERIMETER OF THE BIORETENTION FACILITY BEFORE, DURING, OR AFTER THE PLACEMENT OF THE BIORETENTION SOIL MIX. GROUND PRESSURE SHOULD NOT EXCEED 7 PSI.
8. SOIL SURFACES SHALL BE SCARIFIED TO AERATE AND REDUCE SOIL COMPACTION. SOIL SHALL BE PLACED IN 6" LOOSE DEPTH LIFTS AND LIGHTLY HAND–TAMPED OR COMPACTED WITH A WATER–FILLED LANDSCAPE ROLLER, TO REDUCE POTENTIAL FOR EXCESSIVE SETTLING. NO OTHER MECHANICAL EQUIPMENT SHALL BE USED TO COMPACT THE ENGINEERED SOIL OR UNDERLYING SOILS.
9. LOOSEN SUBGRADE SOILS THAT HAVE BEEN COMPACTED OR SMEARED BY RAKING, DISKING OR TILLING TO A MINIMUM DEPTH OF 6 INCHES.
10. UNIFORMLY GRADE BIORETENTION SOIL MIX TO ACHIEVE A SMOOTH SURFACE. DO NOT OVER–WORK OR EXCESSIVELY COMPACT BIORETENTION SOIL MIX. GRADE TO CROSS SECTIONS, THICKNESS AND ELEVATIONS INDICATED ON PLANS. SETTLING OF SOIL BY WALKING ON SURFACE, WORKING WITH HAND OR LOW GROUND PRESSURE EQUIPMENT (< 7 PSI) IS ACCEPTABLE.
11. DURING EXCAVATION, HEAVY MACHINERY SHOULD NOT DRIVE OVER EXPOSED UNDERLYING SOILS.
12. EXCAVATE IN DRY CONDITIONS AS OFTEN AS PRACTICABLE.
13. USE TRACKED VEHICLES.
14. EXCAVATE FINAL 9"–12" WITH TEETH OF BUCKET (DO NOT SMEAR).
15. SUBSOILS SHALL BE SCARIFIED (NOT COMPACTED) PRIOR TO PLACEMENT OF CLEAN–WASHED AGGREGATE SUBBASE.

N.T.S.

SMALL COMMERCIAL GUIDE TYPICAL DETAILS

BIORETENTION

CITY OF ATLANTA
WATERSHED MANAGEMENT

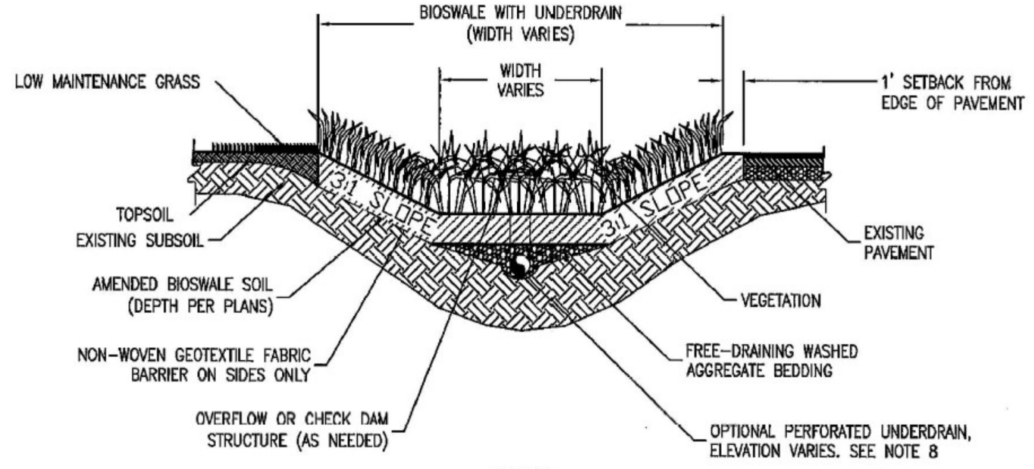
Bioswale

Design Assumptions	
Length (ft)	10.0
Width (ft)	10.0
Area (SF)	100.0
Media Depth (in)	24.0
Gravel Depth (in)	9.0
Ponding Depth (in)	9.0
Total Depth (ft)	3.5

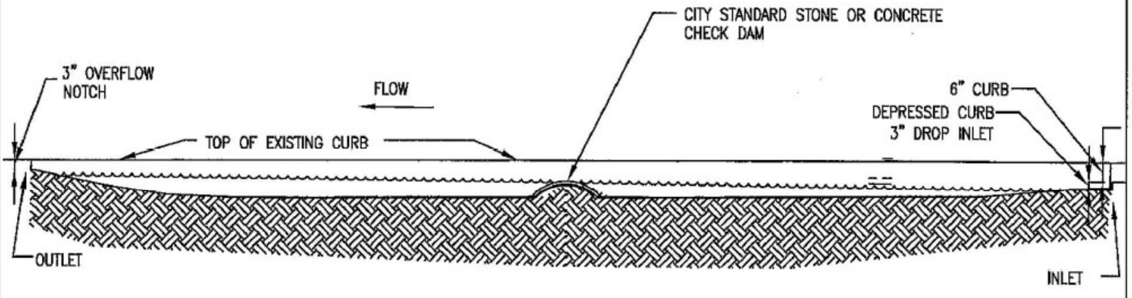
		Unit Prices					
Item / Activity	**Unit**	**2005 Low Estimate**	**2005 High Estimate**	**2005 Average**	**2021 Average**	**QTY**	**Item / Activity Cost**
Excavation	CY	$8.00	$10.00	$9.00	$12.92	13.0	$167.42
Grading	SY	$0.10	$0.15	$0.13	$0.18	22.2	$3.99
Filter Fabric	SF	$0.70	$1.00	$0.85	$1.22	109.4	$133.49
Underdrain Trench (Gravel)	CY	$30.00	$35.00	$32.50	$46.64	0.6	$25.91
Underdrain (Perforated Pipe 8" Dia)	LF	$15.00	$20.00	$17.50	$25.11	10.0	$251.13
Soil Media	CY	$40.00	$60.00	$50.00	$71.75	4.4	$318.89
Seed	SF	$1.00	$2.00	$1.50	$2.15	200.0	$430.50
						Total Cost	**$1,331.32**
						Cost PSF	**$13.31**

Storage Type	Depth (in)	Void Ratio	Storage (CF)
Surface (Ponding)	9.0	-	75.0
Soil	24.0	0.32	64.0
		Total Storage	139.0
		Storage PSF	**1.39**

Calculation Notes:
1. 2005 High and Low Estimates retrieved from: *Low Impact Development for Big Box Retailers, EPA 2005*
2. A CPI inflation factor of 1.435 was used to convert 2005 dollars to 2021 dollars (*https://www.bls.gov/data/inflation_calculator.htm*)
3. Swale is assumed to be trapezoidal in shape with a 2:1 side slope on both sides.
4. Excavation, Grading, and Seeding quantities account for disturbed area along perimeter in addition to bioswale footprint.
5. Filter fabric quantity calculated based on placement along bottom and perimeter of trapezoidal swale
6. Void Ratio retrieved from COA Small Commercial Green Infrastructure Manual
7. Soil Infiltration Rate Assumed to be 0.25 in/hr



SECTION



PROFILE

NOTES:

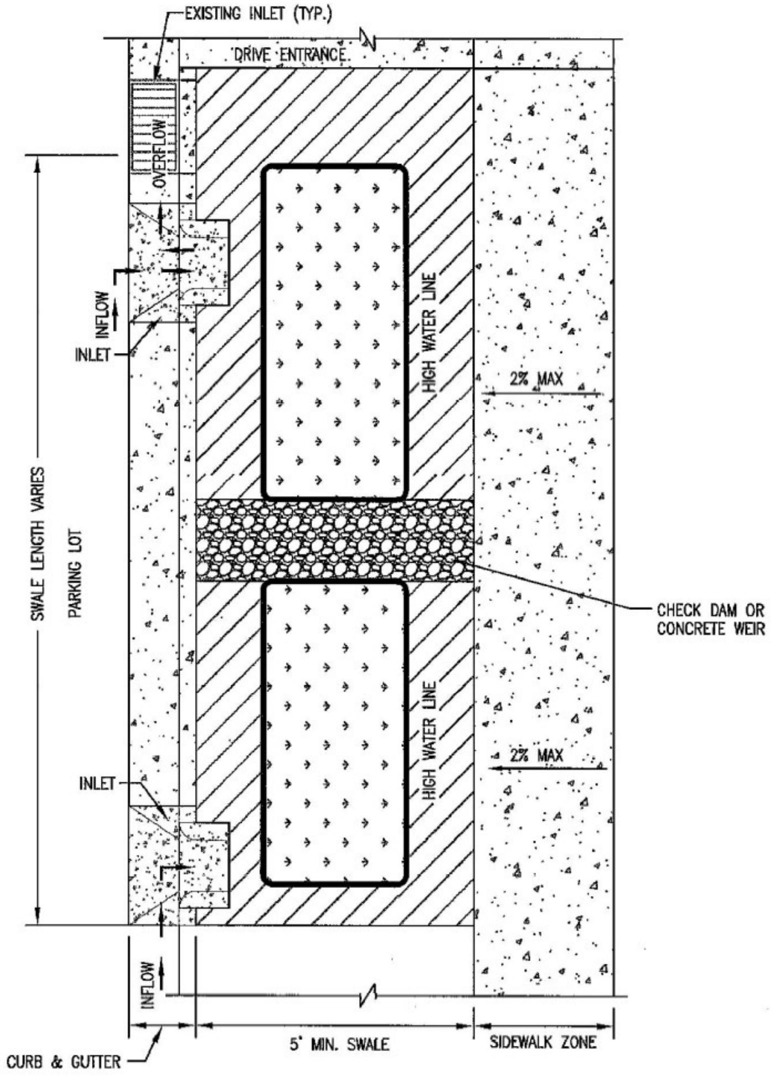
1. IF STORMWATER BIOSWALE IS CONSTRUCTED NEXT TO AN EXISTING SIDEWALK, SOIL ELEVATIONS MUST BE BROUGHT TO TOP OF CURB AND SLOPE AWAY FROM CURB AT A 4:1 SLOPE.
2. STONE CHECK DAMS SHOULD BE CONSTRUCTED OF GRADED SIZE 2–10" STONE. MECHANICAL OR HAND PLACEMENT SHALL BE REQUIRED TO ENSURE COMPLETE COVERAGE OF ENTIRE WIDTH OF BIOSWALE, AND THAT CENTER OF DAM IS LOWER THAN EDGES.
3. DURING EXCAVATION, HEAVY MACHINERY SHOULD NOT DRIVE OVER EXPOSED UNDERLYING SOILS.
4. EXCAVATE IN DRY CONDITIONS AS OFTEN AS PRACTICABLE.
5. USE TRACKED VEHICLES.
6. EXCAVATE FINAL 9"–12" WITH TEETH OF BUCKET (DO NOT SMEAR).
7. SUBSOILS SHALL BE SCARIFIED (NOT COMPACTED) PRIOR TO PLACEMENT OF CLEAN-WASHED AGGREGATE SUBBASE.
8. IF AN UNDERDRAIN IS UTILIZED, IT SHOULD TIE INTO AN UPTURNED "S" UNDERDRAIN (SEE BIOSWALE TABLE B FOR DESIGN VALUES) OR IT SHALL BE INSTALLED ON THE BOTTOM (SEE BIOSWALE TABLE C FOR DESIGN VALUES).

N.T.S.

SMALL COMMERCIAL GUIDE TYPICAL DETAILS

BIOSWALE

CITY OF ATLANTA WATERSHED MANAGEMENT



PLAN

N.T.S.

SMALL COMMERCIAL GUIDE TYPICAL DETAILS

BIOSWALE – CURB & GUTTER

NOTES:

1. INFILTRATION RATE SHALL BE FIELD VERIFIED BY A CERTIFIED PROFESSIONAL. REFER TO APPENDIX C, TESTING PARAMETERS.
2. BIOSWALE SIZE TO BE DETERMINED BY A CIVIL ENGINEER. SIZE SHALL BE BASED ON VOLUME NEEDED FOR STORAGE OF RRv.
3. TYPICAL STORAGE DEPTH FOR BIOSWALE = 9". PLANTINGS SHOULD BE LOCATED ACCORDING TO THEIR WATER TOLERANCE AND ANTICIPATED FLOW DEPTH. WATER SHOULD NOT REMAIN IN BIOSWALE LONGER THAN 48 HRS.
4. GRAVEL AND PERFORATED PIPE UNDERDRAIN SYSTEM
    a. GRAVEL: 8" LAYER ASTM D448 SIZE NO. 57 WASHED STONE AND SHOULD BE SEPARATED BY A THIN 2 TO 4 INCH LAYER OF CHOKER STONE (ASTM D 448 SIZE NO. 8, 3/8" TO 1/8" OR ASTM D 448 SIZE NO. 89, 3/8" TO 1/16")
    b. PERFORATED PIPE: 4 TO 6 INCH PERFORATED PVC (AASHTO M 252), 3/8" PERFORATION SPACED 6" ON CENTER, MIN SLOPE OF 0.5% (NO SOCK PIPES SHALL BE PERMITTED)
    c. NON-WOVEN SEPARATION GEOTEXTILE UTILIZED ON THE SIDE SURFACE INTERFACES ONLY TO PREVENT SOIL MOVEMENT INTO THE SUBBASE.
5. CONNECT UNDERDRAIN PIPES TO STORM SEWER SYSTEM PER PLANS. UNDERDRAIN PIPES SHOULD BE PERFORATED OR SLOTTED AND SIZED BASED ON FLOW RATE. (6" MIN. DIA.).
6. WHERE PERMEABLE PAVEMENTS ARE USED NEAR BIOSWALES, PROTECT STONE BASE UNDER PAVEMENT WITH GEOTEXTILE FABRIC TO PREVENT SOIL MOVEMENT INTO PERMEABLE PAVEMENT BASE. SEE PERMEABLE PAVEMENT DETAIL.
7. WHERE NON-POROUS PAVEMENTS ARE USED NEAR BIOSWALES, PROTECT PAVEMENT BASE WITH IMPERVIOUS LINER TO MINIMIZE WATER MIGRATION UNDER PAVEMENT.
8. BIOSWALES SHALL NOT BE INSTALLED OVER SEPTIC TANK.
9. IF A CURB CUT IS PERFORMED, UTILIZE THE INLET – CURB CUT DETAIL.
10. INSTALL ROCK OR SPLASH BLOCK FOR CONCENTRATED FLOWS ENTERING THE BIOSWALE TO PROTECT AGAINST EROSION.
11. TO PREVENT FAILURE DUE TO SEDIMENT ACCUMULATION, SWALES SHOULD BE INSTALLED AFTER THEIR CONTRIBUTING DRAINAGE AREA (CDA) HAS BEEN COMPLETELY STABILIZED OR STORMWATER SHOULD BE DIVERTED AROUND BIOSWALE UNTIL THE CDA HAS BEEN STABILIZED.
12. EROSION AND SEDIMENT CONTROL MEASURES SHOULD BE USED TO PROTECT BIOSWALES. DIVERT POST-CONSTRUCTION STORMWATER RUNOFF AROUND BIOSWALES UNTIL VEGETATIVE COVER HAS BEEN ESTABLISHED.
13. HEAVY VEHICULAR AND FOOT TRAFFIC SHOULD BE KEPT OUT OF BIOSWALES DURING AND AFTER CONSTRUCTION TO PREVENT SOIL COMPACTION.
14. NATIVE SOILS ALONG BOTTOM OF THE BIOSWALE SHOULD BE TILLED TO 3-4" PRIOR TO PLACEMENT OF AN UNDERDRAIN AND/OR ENGINEERED SOIL MIX.
15. CONSTRUCTION CONTRACTS SHOULD CONTAIN A REPLACEMENT WARRANTY TO HELP ENSURE ADEQUATE GROWTH AND SURVIVAL OF VEGETATION PLANTED.
16. DURING EXCAVATION, HEAVY MACHINERY SHOULD NOT DRIVE OVER EXPOSED UNDERLYING SOILS.
17. EXCAVATE IN DRY CONDITIONS AS OFTEN AS PRACTICABLE.
18. USE TRACKED VEHICLES.
19. EXCAVATE FINAL 9"-12" WITH TEETH OF BUCKET (DO NOT SMEAR).
20. SUBSOILS SHALL BE SCARIFIED (NOT COMPACTED) PRIOR TO PLACEMENT OF CLEAN-WASHED AGGREGATE SUBBASE.

N.T.S.

SMALL COMMERCIAL GUIDE TYPICAL DETAILS

BIOSWALE NOTES

CITY OF ATLANTA
WATERSHED MANAGEMENT

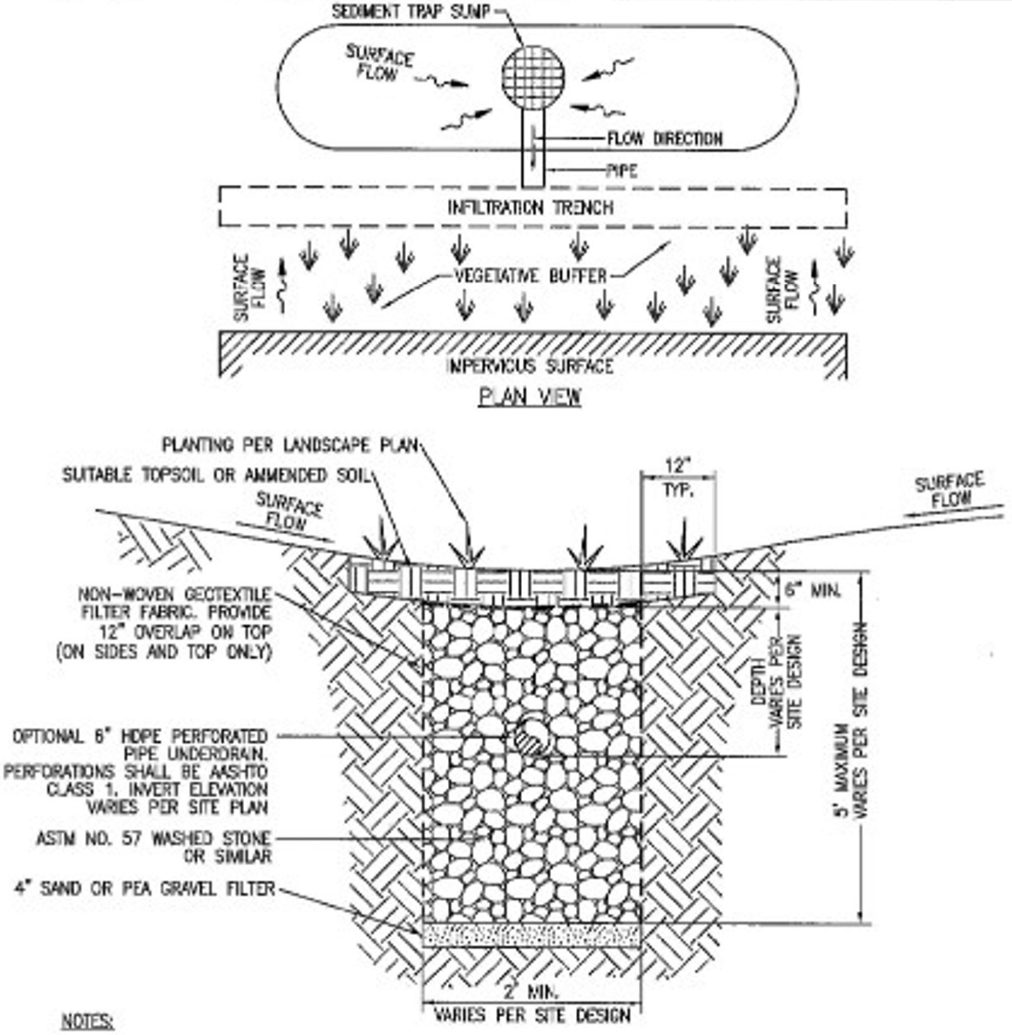
Infiltration Trench

Design Assumptions	
Length (ft)	10.0
Width (ft)	5.0
Area (SF)	50.0
Aggregate Depth (in)	36.0
Total Depth (ft)	3.0

		Unit Prices					
Item / Activity	**Unit**	**2005 Low Estimate**	**2005 High Estimate**	**2005 Average**	**2021 Average**	**QTY**	**Item / Activity Cost**
Excavation	CY	$8.00	$10.00	$9.00	$12.92	5.6	$71.75
Aggregate	CY	$30.00	$35.00	$32.50	$46.64	5.6	$259.10
Filter Fabric	SY	$1.00	$5.00	$3.00	$4.31	15.6	$66.97
Grading	SY	$0.10	$0.15	$0.13	$0.18	22.2	$3.99
Observation Well (4" PVC)	LF	$8.00	$12.00	$10.00	$14.35	3.0	$43.05
Sod	SF	$2.00	$4.00	$3.00	$4.31	50.0	$215.25
						Total Cost	$660.10
						Cost PSF	**$13.20**

Storage Type	Depth (in)	Void Ratio	Storage (CF)
Aggregate	36.0	0.4	60.0
		Total Storage	60.0
		Storage PSF	**1.2**

Calculation Notes:
1. 2005 High and Low Estimates retrieved from: *Low Impact Development for Big Box Retailers, EPA 2005*
2. A CPI inflation factor of 1.435 was used to convert 2005 dollars to 2021 dollars (*https://www.bls.gov/data/inflation_calculator.htm*)
3. Filter Fabric quantity based on placement along bottom and sides of trench
4. Grading quantity based on disturbed area in addition to trench area
5. Void Ratio retrieved from COA Small Commercial Green Infrastructure Manual
6. Soil Infiltration Rate Assumed to be 0.25 in/hr



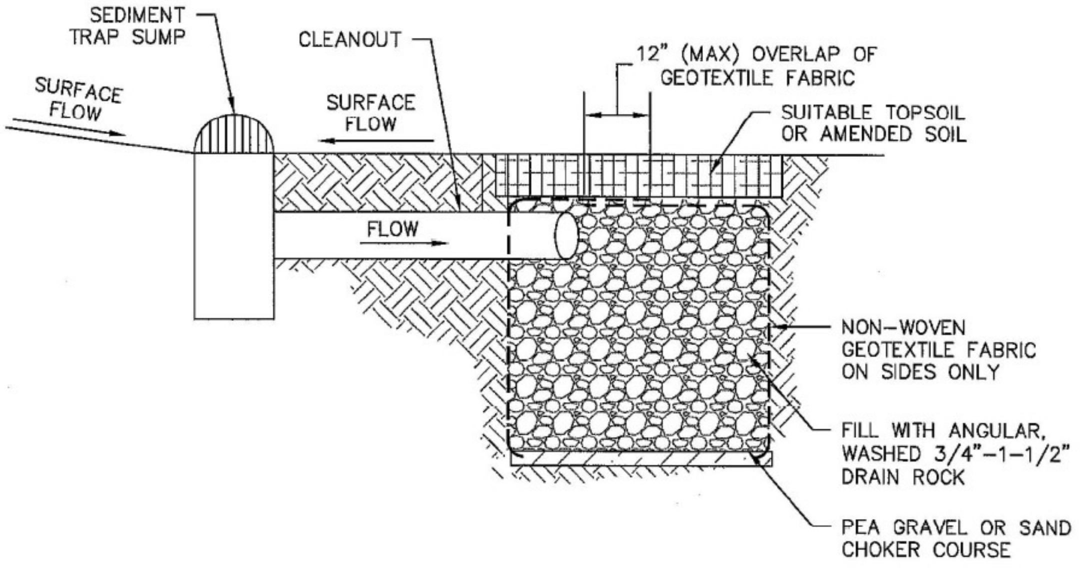
NOTES:

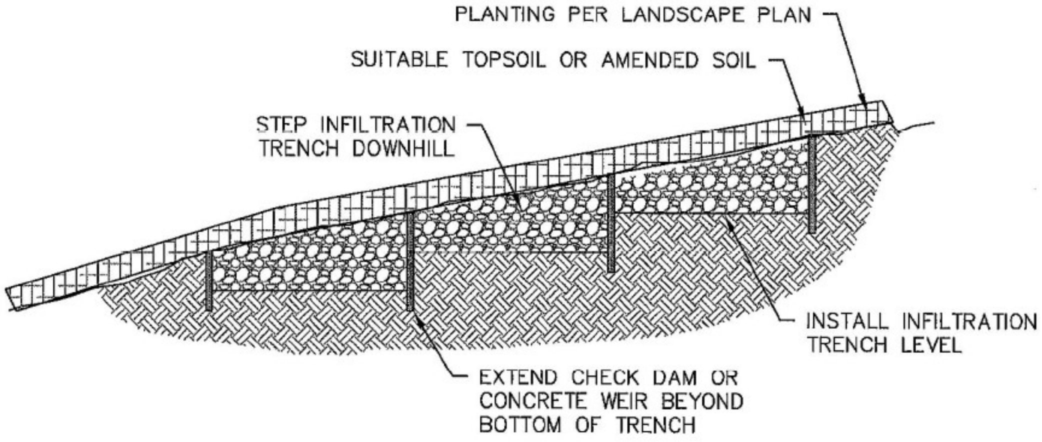
1. PROVIDE 4" TO 6" DIAMETER PVC OBSERVATION WELL TO BOTTOM OF TRENCH.
2. DURING EXCAVATION, HEAVY MACHINERY SHOULD NOT DRIVE OVER EXPOSED UNDERLYING SOILS.
3. EXCAVATE IN DRY CONDITIONS AS OFTEN AS PRACTICABLE.
4. USE TRACKED VEHICLES.
5. EXCAVATE FINAL 9"-12" WITH TEETH OF BUCKET (DO NOT SMEAR).
6. SUBSOILS SHALL BE SCARIFIED (NOT COMPACTED) PRIOR TO PLACEMENT OF CLEAN-WASHED AGGREGATE SUBBASE.

N.T.S.

SMALL COMMERCIAL GUIDE TYPICAL DETAILS

INFILTRATION TRENCH





STEP INFILTRATION TRENCH DOWNHILL
(ON A SLOPE 5% OR GREATER)

N.T.S.

SMALL COMMERCIAL GUIDE TYPICAL DETAILS

STEP INFILTRATION TRENCH

CITY OF ATLANTA
WATERSHED MANAGEMENT

Permeable Pavement

Design Assumptions - Permeable Pavers	
Length (ft)	10.0
Width (ft)	10.0
Area (SF)	100.0
Paver Depth (in)	2.0
Bedding Depth (in)	2.0
Base Course (in)	6.0
Subbase / Storage Course (in)	36.0
Choker Course (in)	4.0
Subgrade Depth (in)	6.0
Total Depth (ft)	4.7

Design Assumptions - Porous Concrete	
Length (ft)	10.0
Width (ft)	10.0
Area (SF)	100.0
Concrete Depth	8.0
Base Course (in)	6.0
Subbase / Storage Course (in)	36.0
Choker Course (in)	4.0
Subgrade Depth (in)	6.0
Total Depth (ft)	5.0

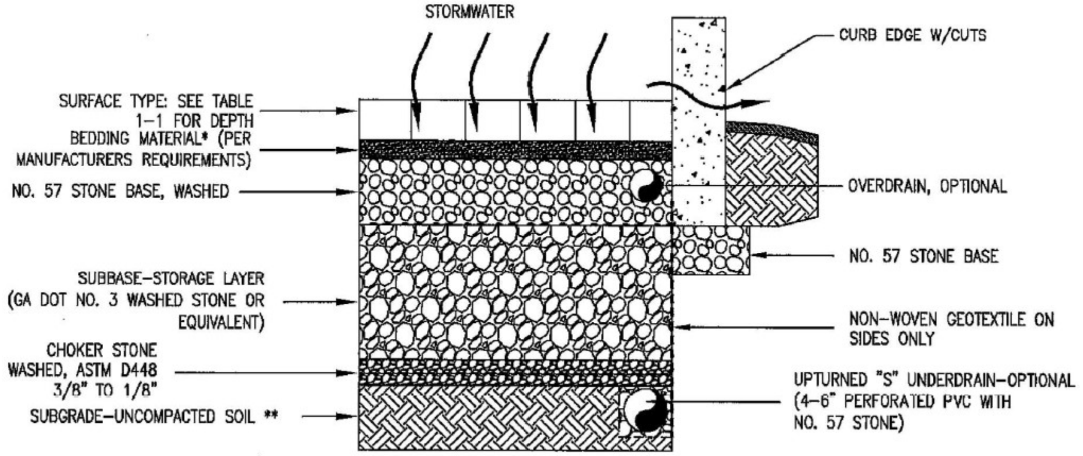
		Unit Prices					
Item / Activity	**Unit**	**2005 Low Estimate**	**2005 High Estimate**	**2005 Average**	**2021 Average**	**QTY**	**Item / Activity Cost**
Excavation	CY	$8.00	$10.00	$9.00	$12.92	17.3	$223.22
Aggregate	CY	$30.00	$35.00	$32.50	$46.64	14.8	$690.93
Filter Fabric	SY	$1.00	$5.00	$3.00	$4.31	20.7	$89.29
Concrete Paving Blocks	SF	$5.00	$10.00	$7.50	$10.76	100.0	$1,076.25
						Total Cost	$2,079.69
						Cost PSF	**$20.80**

		Unit Prices					
Item / Activity	**Unit**	**2005 Low Estimate**	**2005 High Estimate**	**2005 Average**	**2021 Average**	**QTY**	**Item / Activity Cost**
Excavation	CY	$8.00	$10.00	$9.00	$12.92	18.5	$239.17
Aggregate	CY	$30.00	$35.00	$32.50	$46.64	14.2	$662.14
Filter Fabric	SY	$1.00	$5.00	$3.00	$4.31	22.2	$95.67
Porous Concrete	SF	$2.00	$6.50	$4.25	$6.10	100.0	$609.88
						Total Cost	$1,606.85
						Cost PSF	**$16.07**

Storage Type	Depth (in)	Void Ratio	Storage (CF)
Aggregate	36.0	0.4	60.0
		Total Storage	60.0
		Storage PSF	**1.2**

Calculation Notes:

1. 2005 High and Low Estimates retrieved from: *Low Impact Development for Big Box Retailers, EPA 2005*
2. A CPI inflation factor of 1.435 was used to convert 2005 dollars to 2021 dollars (*https://www.bls.gov/data/inflation_calculator.htm*)
4. Aggregate quantity includes aggregate for bedding, base, subbase, and choker courses when applicable
5. Filter Fabric quantity based on placement along sides of excavation only
6. Void Ratio retrieved from COA Small Commercial Green Infrastructure Manual
7. Soil Infiltration Rate Assumed to be 0.25 in/hr



PERMEABLE PAVEMENT SYSTEM

NOTE: WHERE NATIVE SOILS HAVE AN INFILTRATION RATE < 0.25 IN/HR AN UNDERDRAIN IS REQUIRED. UPTURNED "S" UNDERDRAIN SHALL BE USED TO RECEIVE RRv CREDIT FOR RUNOFF CAPTURE AND STORAGE. STONE STORAGE LAYER SHALL DRAIN WITHIN 48 HOURS.

TABLE 1-1

DEPTH REQUIRED FOR EACH LAYER

SURFACE TYPE	SURFACE***	BEDDING MATERIAL	BASE	CHOKER	UNDERDRAIN
PERVIOUS CONCRETE	4–8"	N/A	6"	2–4"	4"–6"
PERVIOUS ASPHALT	3–7"	N/A	6"	2–4"	4"–6"
INTERLOCKING PAVERS	1.5–3"	2"	6"	2–4"	4"–6"
CONCRETE GRID PAVERS	3.5"	1–1.5"	6"	2–4"	4"–6"
PLASTIC GRID PAVERS	3.5"	1–1.5"	6"	2–4"	4"–6"

SUBBASE DEPTH MUST EXCEED MANUFACTURER'S MINIMUM FOR TRAFFIC LOADING DESIGN. ADDITIONAL DEPTH FOR STORAGE AS NEEDED

* CONCRETE AND ASPHALT SURFACE TYPES DO NOT REQUIRE BEDDING MATERIAL.
** MINIMIZE COMPACTION OF SUBGRADE SOILS. SCARIFY OR TILL SUBGRADE TO A DEPTH OF 3–4".
*** PERMEABLE PAVEMENT SURFACE MUST BE ABLE TO SUPPORT THE MAXIMUM PROJECTED TRAFFIC LOAD.

N.T.S.

SMALL COMMERCIAL GUIDE TYPICAL DETAILS

PERMEABLE PAVEMENT

NOTES:

1. DIMENSIONS LISTED ARE MINIMUMS. DESIGNER MUST VERIFY PAVEMENT DEPTH.
2. MINIMUM STONE BASE DEPTH = 6" NO. 57 STONE, WASHED, OR OTHER APPROVED MATERIAL.
3. COMPACTION TO BE MINIMUM REQUIRED FOR STABLE BASE TO ENSURE INFILTRATION CAPACITY. ENGINEER TO SPECIFY REQUIREMENTS BASED ON SITE CONDITIONS AND GEOTECHNICAL REPORT.
4. UPTURNED "S" UNDERDRAIN SHALL BE USED TO RECEIVE RRv CREDIT FOR RUNOFF CAPTURE AND STORAGE. STONE STORAGE LAYER SHALL DRAIN WITHIN 48 HOURS.
5. INFILTRATION RATE SHALL BE FIELD VERIFIED BY CERTIFIED PROFESSIONAL. REFER TO THE CITY OF ATLANTA STORMWATER MANAGEMENT PRACTICES FOR SMALL COMMERCIAL DEVELOPMENT – APPENDIX C – INFILTRATION TESTING PARAMETERS.
6. USE NON-WOVEN GEOTEXTILE FABRIC ON SIDES OF STONE STORAGE LAYER.
7. PERMEABLE PAVEMENT SYSTEM MUST BE CLEARLY MARKED ON DEVELOPMENT PLAN AND A NOTE TO PROTECT WITH TEMPORARY CONSTRUCTION FENCING.
8. EXCAVATION MUST BE CONSTRUCTED TO SPECIFIED WIDTH AND DEPTH OF PERMEABLE PAVEMENT SYSTEM, STOCKPILED MATERIAL SHOULD BE CLEARLY STORED AWAY FROM EXCAVATION.
9. NATIVE SOILS ALONG BOTTOM OF THE PERMEABLE PAVEMENT SYSTEM SHOULD BE TILLED OR SCARIFIED TO 3–4" PRIOR TO PLACEMENT OF CHOKER STONE.
10. SIDES OF EXCAVATIONS MUST BE TRIMMED OF LARGE ROOTS THAT WILL HAMPER INSTALLATION OF FILTER FABRIC AROUND THE STONE STORAGE.
11. WHEN USING PORTLAND CEMENT PERVIOUS CONCRETE (PCPC), THE PAVEMENT SHALL REMAIN COVERED FOR 7 DAYS DURING THE CURING PERIOD. NOT REQUIRED FOR PAVERS OR POROUS ASPHALT.
    a. DURING THIS TIME IT IS CRITICAL THAT ANY STORMWATER BE DIVERTED AWAY FROM THE PAVEMENT.
12. ADEQUATE EROSION CONTROL MUST BE PROVIDED. SEDIMENT LADEN STORMWATER SHALL NOT BE ALLOWED TO FLOW IN THE PERMEABLE PAVEMENT AREA.
13. NO MULCH OR LANDSCAPING STORAGE SHALL BE ALLOWED ON THE PAVEMENT AREAS.
14. PERMEABLE PAVEMENT MUST BE TESTED AFTER CONSTRUCTION. AFTER PLACEMENT AND APPROPRIATE CURING OF STRUCTURAL PAVEMENT SURFACE (7 DAYS FOR PERVIOUS CONCRETE AND 48 HOURS MINIMUM FOR POROUS ASPHALT HARDENING), TEST INFILTRATION ABILITY BY APPLYING CLEAN WATER AT A RATE OF AT LEAST 5 GPM OVER SURFACE. THE WATER APPLIED TO THE SURFACE SHOULD INFILTRATE WITHOUT CREATING PUDDLES OR RUNOFF.
17. DURING EXCAVATION, HEAVY MACHINERY SHOULD NOT DRIVE OVER EXPOSED UNDERLYING SOILS.
18. EXCAVATE IN DRY CONDITIONS AS OFTEN AS PRACTICABLE.
19. USE TRACKED VEHICLES.
20. EXCAVATE FINAL 9"–12" WITH TEETH OF BUCKET (DO NOT SMEAR).
21. SUBSOILS SHALL BE SCARIFIED (NOT COMPACTED) PRIOR TO PLACEMENT OF CLEAN-WASHED AGGREGATE SUBBASE.
22. GRAVEL BASE SHOULD BE COMPACTED WITH A 10 TON ROLLER UNTIL THERE IS NO VISIBLE MOVEMENT.

N.T.S.

SMALL COMMERCIAL GUIDE TYPICAL DETAILS

PERMEABLE PAVEMENT

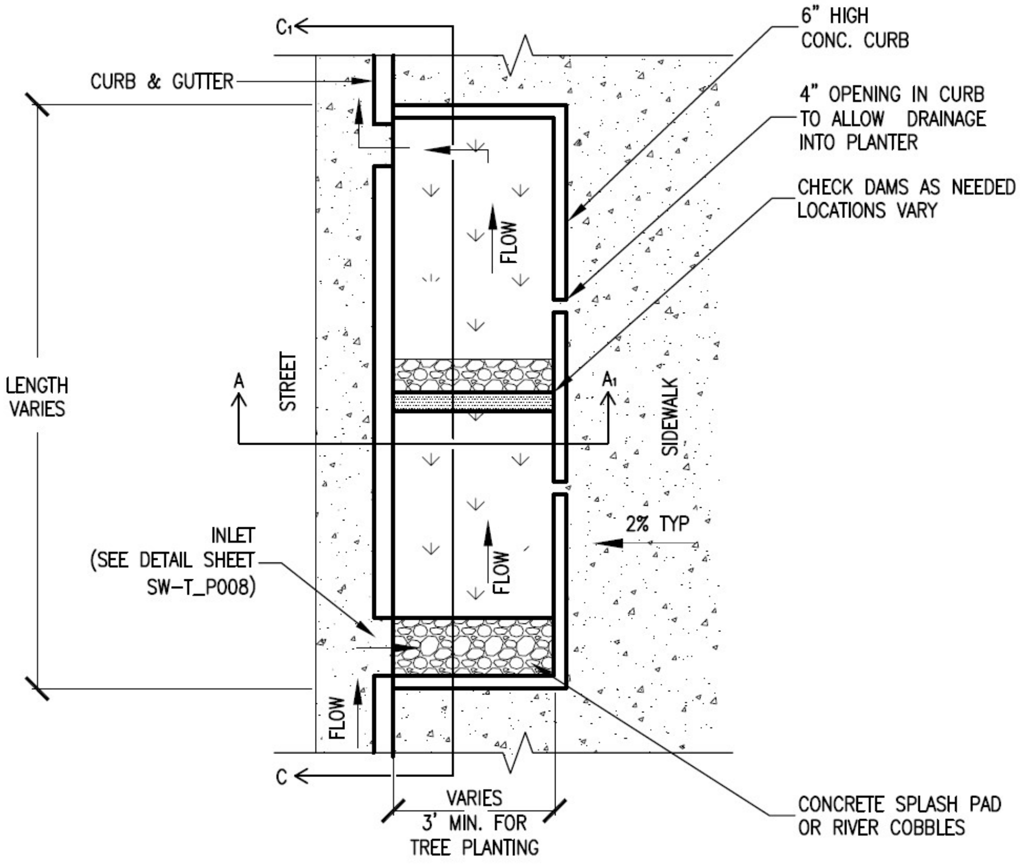
Stormwater Planter

Design Assumptions	
Length (ft)	10.0
Width (ft)	10.0
Area (SF)	100.0
Media Depth (in)	36.0
Gravel Depth (in)	12.0
Mulch Depth (in)	3.0
Ponding Depth (in)	9.0
Total Depth (ft)	5.0

		Unit Prices					
Item / Activity	**Unit**	**2005 Low Estimate**	**2005 High Estimate**	**2005 Average**	**2021 Average**	**QTY**	**Item / Activity Cost**
Excavation	CY	$8.00	$10.00	$9.00	$12.92	18.5	$239.17
Concrete Planter Box	CY	$75.00	$125.00	$100.00	$143.50	1.5	$212.59
Geotextile Fabric	SF	$1.00	$5.00	$3.00	$4.31	200.0	$861.00
Underdrain Trench (Gravel)	CY	$30.00	$35.00	$32.50	$46.64	3.7	$172.73
Underdrain (Perforated Pipe 8" Dia)	LF	$15.00	$20.00	$17.50	$25.11	10.0	$251.13
Mulch	CY	$30.00	$35.00	$32.50	$46.64	0.9	$43.18
Soil Media	CY	$15.00	$25.00	$20.00	$28.70	11.1	$318.89
Plants	Ea	$5.00	$20.00	$12.50	$17.94	66.7	$1,195.83
						Total Cost	**$3,294.52**
						Cost PSF	**$32.95**

Storage Type	**Depth (in)**	**Void Ratio**	**Storage (CF)**
Surface (Ponding)	9.0	-	75.0
Soil	36.0	0.32	80.0
		Total Storage	155.0
		Storage PSF	**1.71**

Calculation Notes:
1. 2005 High and Low Estimates retrieved from: *Low Impact Development for Big Box Retailers, EPA 2005*
2. A CPI inflation factor of 1.435 was used to convert 2005 dollars to 2021 dollars (*https://www.bls.gov/data/inflation_calculator.htm*)
3. Concrete planter box assumed to be 36” deep, 4” wide around entire perimeter
4. Geotextile liner is placed over top and beneath aggregate layer in lieu of choker stone
5. Plant spacing assumed to be 1.5’ on center
6. Void Ratio retrieved from COA Small Commercial Green Infrastructure Manual
7. Soil Infiltration Rate Assumed to be 0.25 in/hr



SEE SHEETS SW-T_P003 AND SW-T_P004 FOR SECTIONS

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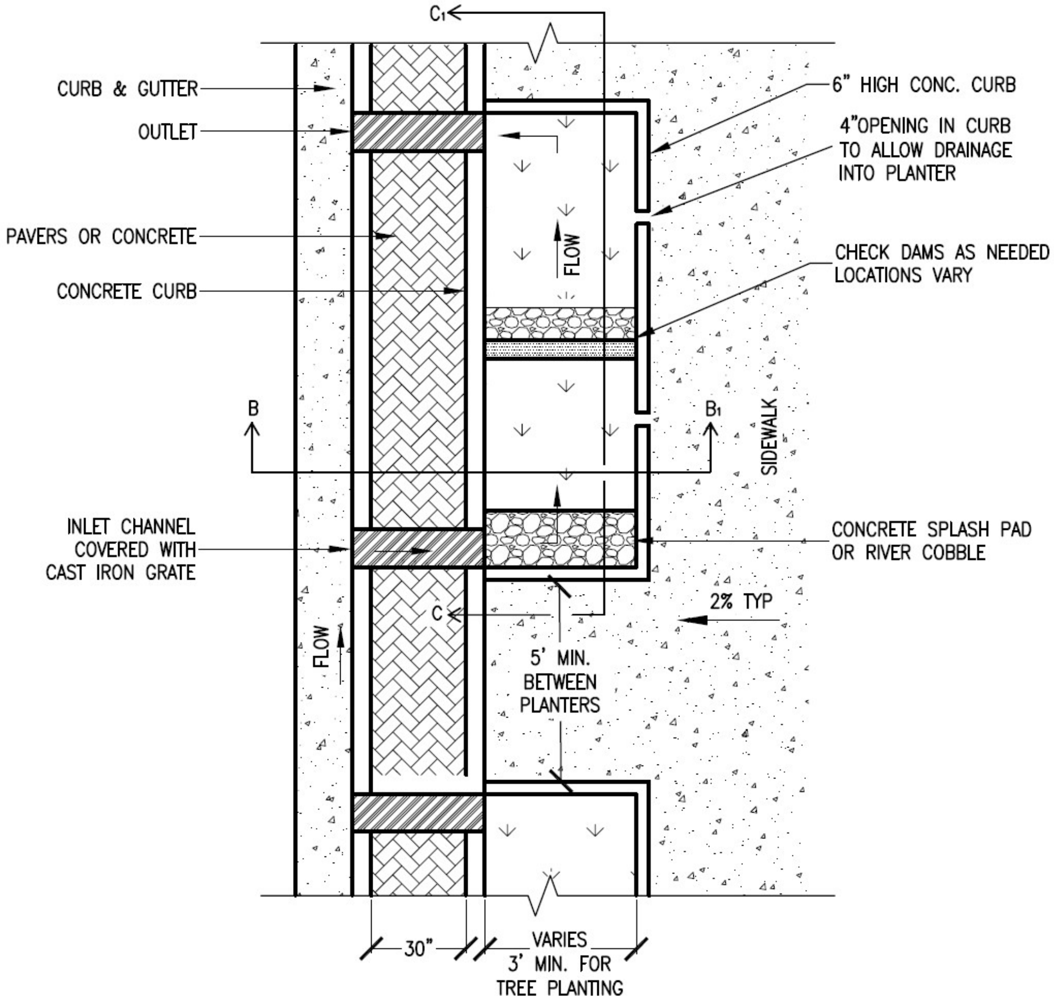
City of Atlanta

STANDARD DETAILS

STORMWATER PLANTER
NO ON-STREET PARKING

REV.
DATE: APRIL 2012
ORIG. DATE:
SCALE: N.T.S.

DETAIL NO. SW-T_P001



SEE SHEETS SW–T_P003 AND SW–T_P004 FOR SECTIONS

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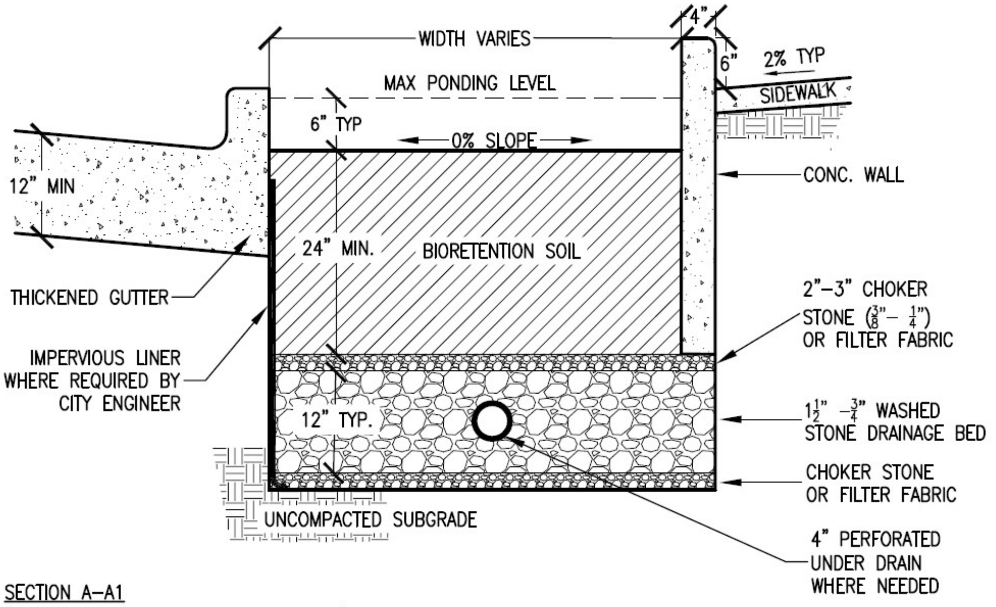
City of Atlanta

STANDARD DETAILS

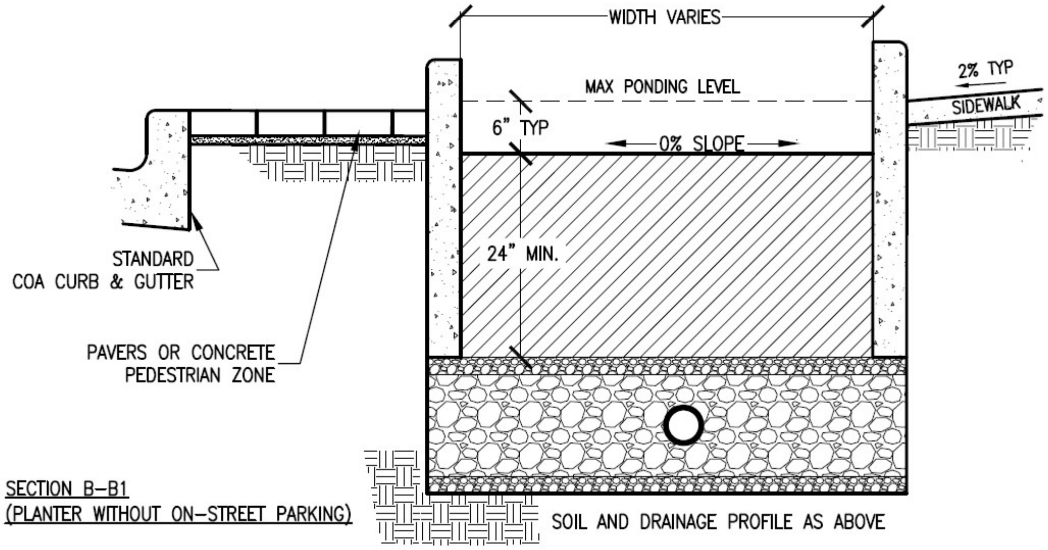
STORMWATER PLANTER
WITH ON–STREET PARKING

REV.
DATE: APRIL 2012
ORIG. DATE:
SCALE: N.T.S.

DETAIL NO.SW–T_P002



SECTION A–A1
(PLANTER WITHOUT ON–STREET PARKING)



SECTION B–B1
(PLANTER WITHOUT ON–STREET PARKING)

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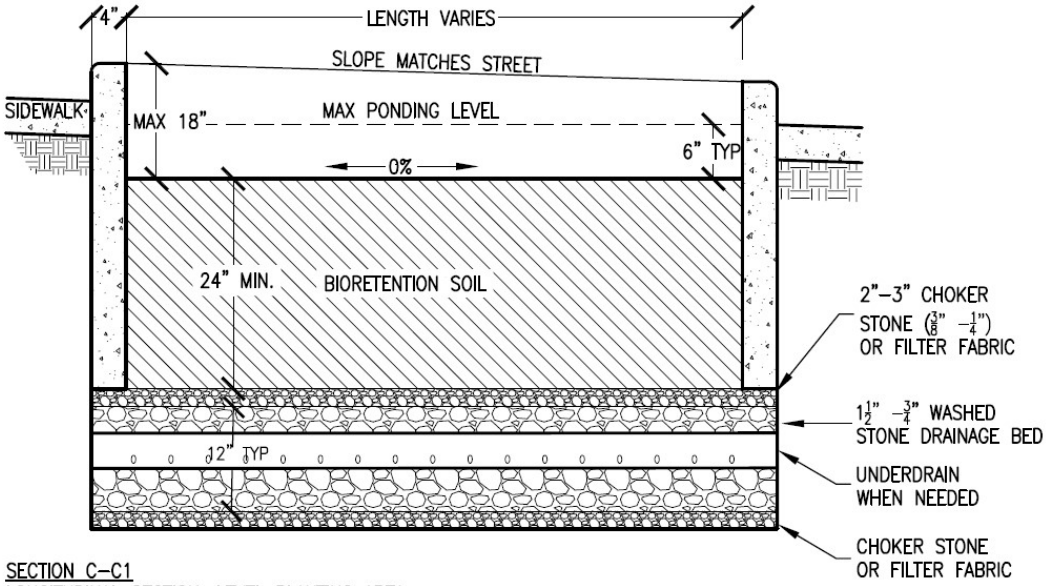
City of Atlanta

STANDARD DETAILS

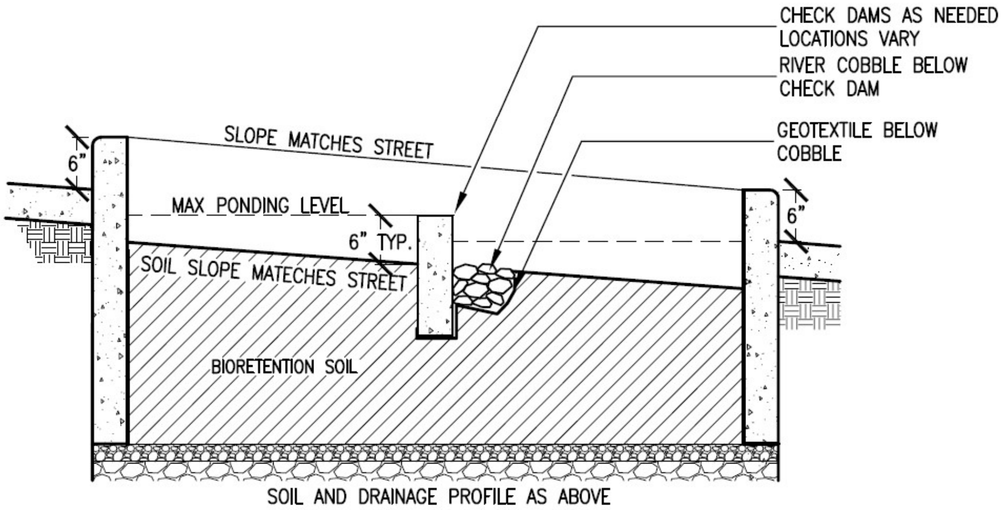
STORMWATER PLANTER
SECTIONS

REV.
DATE: APRIL 2012
ORIG. DATE: NOV 2004
SCALE: N.T.S.

DETAIL NO. SW–T_P003



SECTION C–C1
LONGITUDINAL SECTION, LEVEL PLANTING AREA



SECTION C–C1
LONGITUDINAL SECTION, SLOPED PLANTING AREA

NOTE: IF SLOPES OF STREET AND SIDEWALK ALLOW, PLANTERS SHOULD BE BUILT WITH LEVEL PLANTING AREAS

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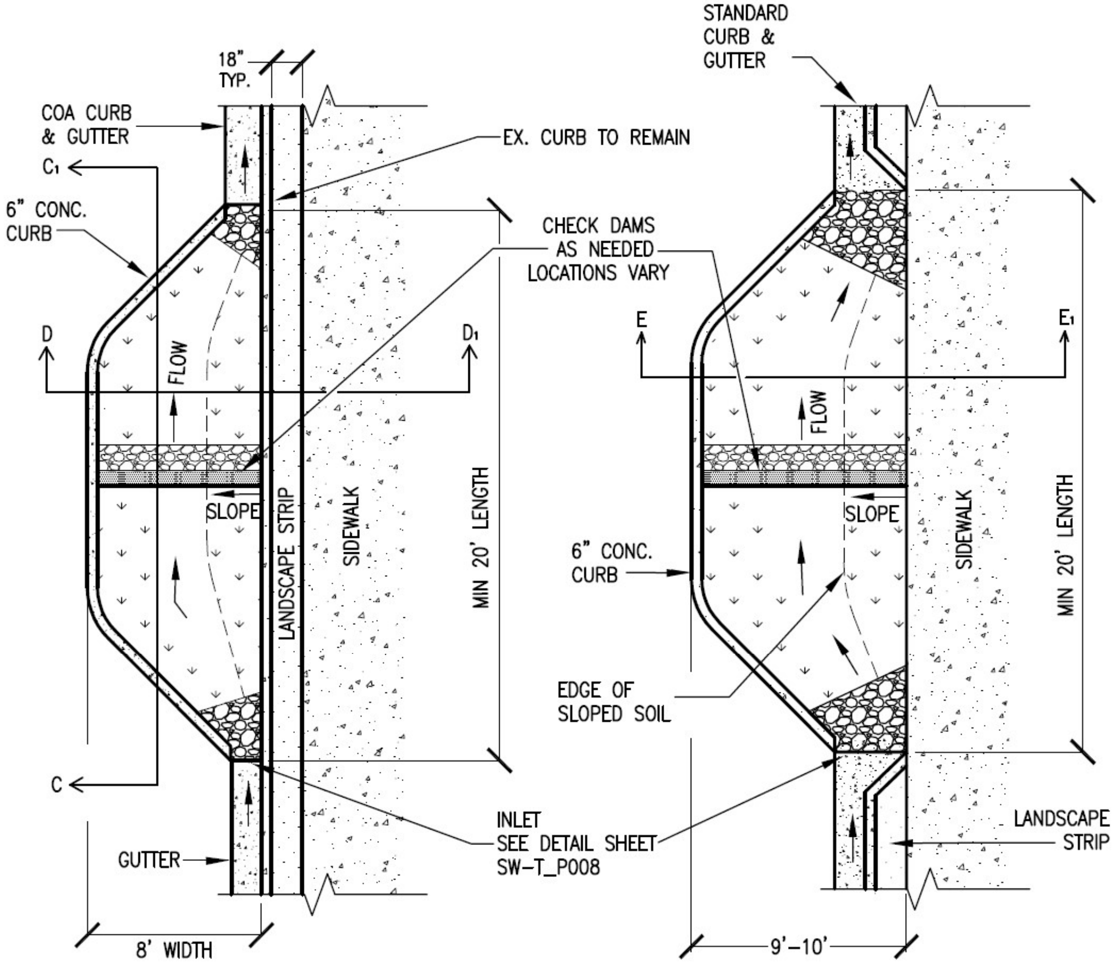
City of Atlanta

STANDARD DETAILS

STORMWATER PLANTER
LONGITUDINAL SECTIONS

REV.
DATE: APRIL 2012
ORIG. DATE:
SCALE: N.T.S.

DETAIL NO. SW-T_P004



SEE SHEETS SW-T_P004 AND SW-T_P007 FOR SECTIONS

"BULB-OUT"/CURB EXTENSION
NOT EXTENDING INTO LANDSCAPE STRIP

"BULB-OUT"/CURB EXTENSION
EXTENDING INTO LANDSCAPE STRIP

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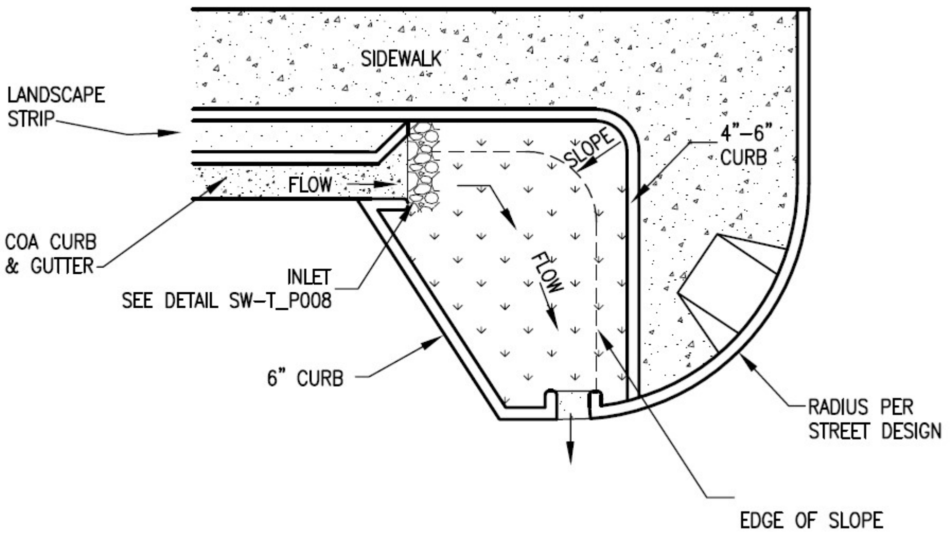
City of Atlanta

STANDARD DETAILS

STORMWATER
PLANTER'BULB-OUTS"/ CURB
EXTENSIONS

REV.
DATE: APRIL 2012
ORIG. DATE:
SCALE: N.T.S.

DETAIL NO. SW-T_P005



"BULB–OUT"/CURB EXTENSION AT INTERSECTION, TYPICAL PLAN

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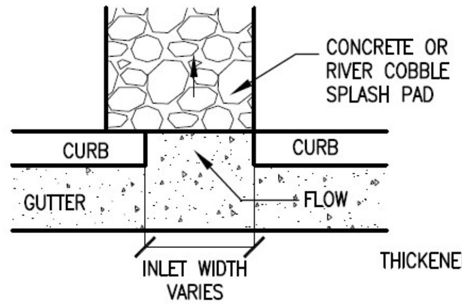
City of Atlanta

STANDARD DETAILS

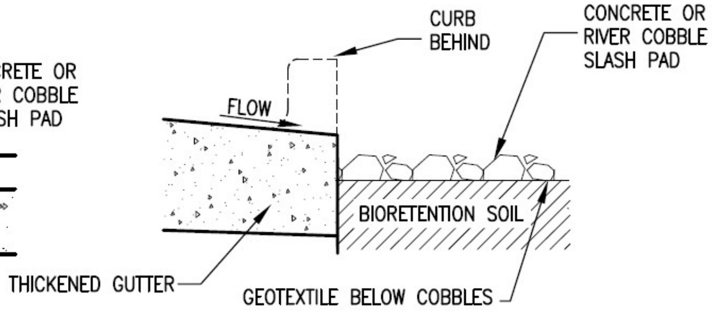
STORMWATER PLANTER "BULB–OUT" AT INTERSECTION

REV.
DATE: APRIL 2012
ORIG. DATE:
SCALE: N.T.S.

DETAIL NO. SW–T_P006



PLANTER INLET– PLAN



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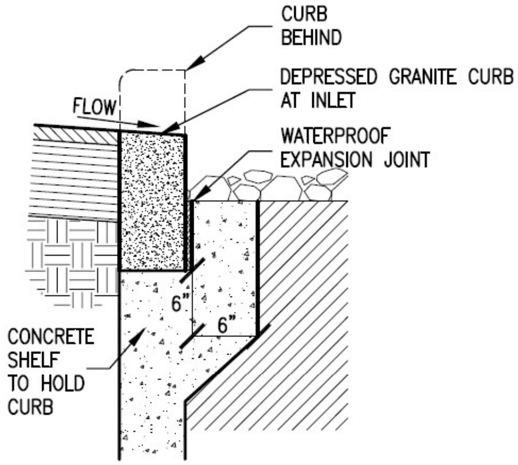
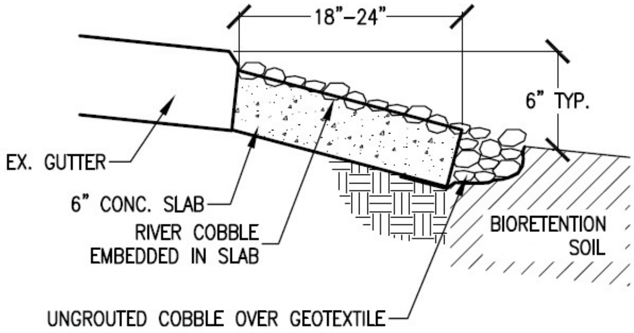


INLET AT GRANITE CURB

NOTES:

1) SIZE INLETS TO ACCOMMODATE DESIRED FLOWS.

2) INLETS & GUTTER MAY BE MODIFIED TO ADJUST FLOW INTO PLANTER.



FOR 'BULB OUTS'/ CURB EXTENSIONS

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STANDARD DETAILS

STORMWATER PLANTER
INLET DETAILS

REV.
DATE: APRIL 2012
ORIG. DATE:
SCALE: N.T.S.

DETAIL NO. SW–T_P008

NOTES FOR STORMWATER PLANTERS

1. WIDTH AND LENGTH OF PLANTER IS BASED ON SITE CONDITIONS AND STORMWATER TREATMENT VOLUME.

2. LOCATE ALL UTILITIES PRIOR TO DESIGN. SITE CONDITIONS WILL VARY AND SIGNIFICANT DESIGN ADAPTATIONS MAY BE NEEDED TO ADDRESS UTILITY CONFLICTS, STEEP SLOPES, AND OTHER CONSTRAINTS.

3. IF SLOPE OF ROAD AND SIDEWALK ALLOW, PLANTERS SHOULD BE BUILT WITH LEVEL PLANTING AREAS (0% SLOPE LONGITUDINALLY) FOR MAXIMUM STORMWATER TREATMENT VOLUME.

4. LONGITUDINAL SLOPES OF CURBS SURROUNDING PLANTER MATCH ROAD. LEVEL BOTTOM PLANTERS HAVE A MAXIMUM DEPTH OF 18" BELOW SURROUNDING CURB AT DEEPEST POINT.

5. CROSS SLOPES SHOULD ALWAYS BE AS CLOSE TO LEVEL (0% SLOPE) AS POSSIBLE.

6. CURBS, GUTTERS, STREETS, AND SIDEWALKS SHALL CONFORM TO CITY OF ATLANTA STANDARDS.

7. PROVIDE ELEVATIONS AT ALL INLETS AND OUTLETS, AS WELL AS ALL GRADES ON STREET AND BOTTOM OF PLANTER.

S. SIDEWALK ELEVATION MUST BE HIGHER THAN MAXIMUM FLOW OR POOL ELEVATION.

9. PLANTERS MUST BE ABLE TO WITHSTAND STORMWATER FLOWS WITHOUT EROSION OR OTHER DAMAGE. INLETS SHOULD BE SIZED AND CHECK DAMS USED TO ENSURE APPROPRIATE VELOCITIES.

10. ALL PLANTERS MUST BE FULLY VEGETATED. SUGGESTED SPECIES. CAN BE FOUND IN THE GEORGIA STORMWATER MANAGEMENT MANUAL, VOL. 2, APPENDIX F.

11. ALL VEGETATED AREAS MUST BE MULCHED WITH EITHER 2–3" OF NON–FLOATABLE ORGANIC MULCH (SUCH AS SHREDDED HARDWOOD OR LEAF MOULD) OR STONE. STONE MULCH MAY BE NEEDED IN AREAS OF STRONG FLOWS TO PREVENT EROSION. ALL PONDING ELEVATIONS SHOWN IN DETAILS ARE ASSUMED TO BE MEASURRED FROM TOP OF MULCH LAYER

12. BIORETENTLON SOIL MUST CONFORM TO PERFORMANCE STANDARDS DETAILED IN SPECIFICATIONS.

13. BIORETENTION SOIL MUST BE A MIN. OF 24" DEEP AT SHALLOWEST POINT. 36" DEPTH IS REQUIRED FOR PLANTING TREES.

14. UNDERDRAINS MAY BE REQUIRED UNLESS INFILTRATION TESTS IN SOILS AT BOTTOM OF PLANTER SHOW SATURATED INFILTRATION RATES OF GREATER THAN ½ INCH PER HOUR (1 FOOT/DAY).

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City of Atlanta

STANDARD DETAILS

STORMWATER PLANTER
NOTES

REV.
DATE: APRIL 2012
ORIG. DATE:
SCALE: N.T.S.

DETAIL NO. SW–T_P009

Subsurface Infiltration and Detention

Design Assumptions	
Length (ft)	30.0
Width (ft)	50.0
Area (SF)	1500.0
Aggregate Depth (in)	12.0
Chamber Height (in)	36.0
Native Soil Backfill (in)	12.0
Total Depth (ft)	5.0

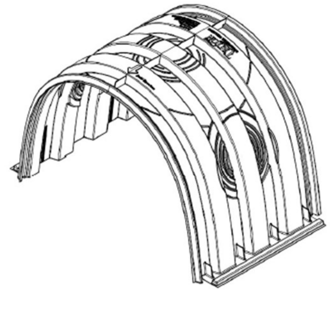
		Unit Prices					
Item / Activity	Unit	2005 Low Estimate	2005 High Estimate	2005 Average	2021 Average	QTY	Item / Activity Cost
Excavation	CY	$8.00	$10.00	$9.00	$12.92	205.0	$2,647.58
Aggregate	CY	$30.00	$35.00	$32.50	$46.64	123.0	$5,736.41
Filter Fabric	SY	$1.00	$5.00	$3.00	$4.31	2025.0	$8,717.63
Grading	SY	$0.10	$0.15	$0.13	$0.18	666.7	$119.58
Chambers (S-29)	Ea	-	-	-	$88.50	80.0	$7,080.00
End Caps (S-29)	Ea	-	-	-	$55.00	10.0	$550.00
Inlet Structure	Ea	-	-	-	$3,500.00	2.0	$7,000.00
Inlet / Outlet Piping (24 in Dia)	LF	-	-	-	$14.00	10.0	$140.00
Chamber Connection Piping (8" Dia)	LF	-	-	-	$16.50	14.0	$231.00
Sod	SF	$2.00	$4.00	$3.00	$4.31	1500.0	$6,457.50
						Total Cost	$38,679.70
						Cost PSF	**$25.79**

Storage Type	Depth (in)	Void Ratio	Storage (CF)
Chamber*	36.0	-	3284.00
End Cap*	36.0	-	49.80
		Total Storage	3333.80
		Storage PSF	**2.22**

Calculation Notes:

*Chamber and End Cap Storage Account for Aggregate Storage with 6” Below and 6” On Top of Chambers with 7.5” spacing between chambers. See Standard details for more information.

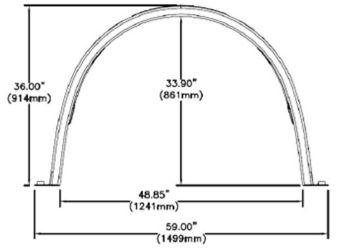
1. 2005 High and Low Estimates retrieved from: *Low Impact Development for Big Box Retailers, EPA 2005*
2. A CPI inflation factor of 1.435 was used to convert 2005 dollars to 2021 dollars (*https://www.bls.gov/data/inflation_calculator.htm*)
4. Aggregate, Filter Fabric, Chamber, End Cap, Inlet/Outlet Piping and Chamber Connection Piping quantities based on estimate received from Triton for 30x50 Underground Detention Area
5. Chamber, End Cap, Inlet/Outlet Piping, Chamber Connection Piping unit costs based on estimate received from Triton

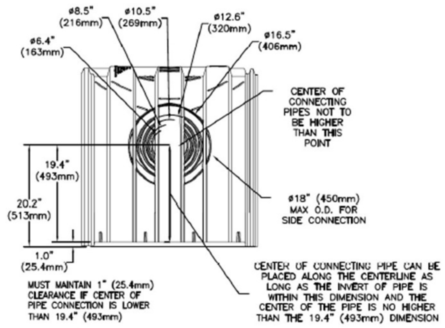


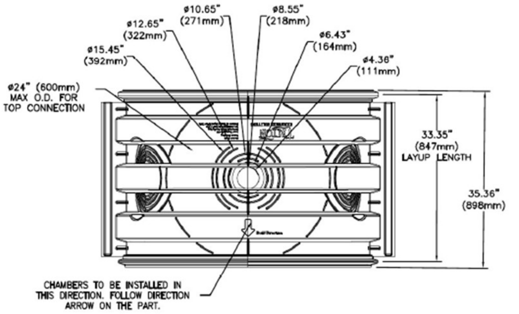
S-29 CHAMBER SPECS	
NOMINAL DIMENSIONS (LAYUP LENGTH X WIDTH X HEIGHT)	33.35" X 59.00" X 36.00" (847mm X 1499mm X 914mm)
BARE CHAMBER STORAGE	27.35 CUBIC FEET (0.774 CUBIC METERS)
*MIN INSTALLED STORAGE	41.05 CUBIC FEET (1.162 CUBIC METERS)
CHAMBER WEIGHT	32 lbs (14.515 kg)
STORAGE PER LINEAR FOOT WITHOUT STONE	9.84 CUBIC FEET (0.279 CUBIC METERS)
STORAGE PER LINEAR FOOT WITH STONE	14.77 CUBIC FEET (0.418 CUBIC METERS)

*ASSUMING A MIN OF 6" (152mm) STONE ABOVE AND BELOW AND 7.5" (191mm) BETWEEN ROWS WITH 40% STONE POROSITY (DOES NOT INCLUDE 12" (305mm) PERIMETER STONE VOLUME)

NOTE: S-29 CHAMBER DETAILS TESTED AND RATED FOR H-30 LOAD CONDITIONS WITH 18" (457mm) OF COVER AND NO PAVEMENT.







CONCEPTUAL PLAN DISCLAIMER
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S-29 CHAMBER DETAIL

TRITON - STANDARD DETAILS

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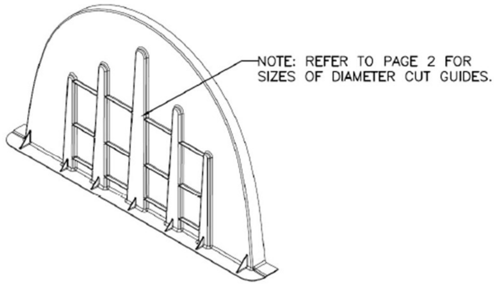
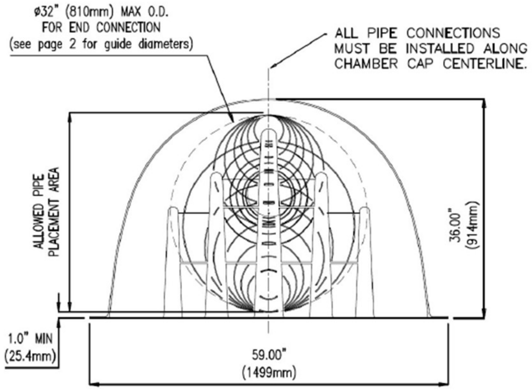
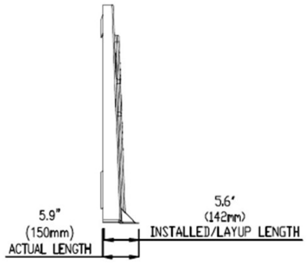
02-26-16 JWM



S-29 END CAP SPECS	
NOMINAL DIMENSIONS (LAYUP LENGTH X WIDTH X HEIGHT)	5.90" X 59.00" X 36.00" (150mm X 1499mm X 914mm)
BARE END CAP STORAGE	1.031 CUBIC FEET (0.029 CUBIC METERS)
*MIN INSTALLED STORAGE	4.98 CUBIC FEET (0.141 CUBIC METERS)

*ASSUMING A MIN OF 6" (152mm) STONE ABOVE AND BELOW AND 7.5" (191mm) BETWEEN ROWS WITH 40% STONE POROSITY (DOES NOT INCLUDE 12" (305mm) PERIMETER STONE VOLUME)





THE END CAP FITS UP ON THE OUTSIDE OF THE S-29 CHAMBER. REFER TO INSTALLATION MANUAL FOR FURTHER DETAIL.

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S-29 CHAMBER END CAP DETAIL

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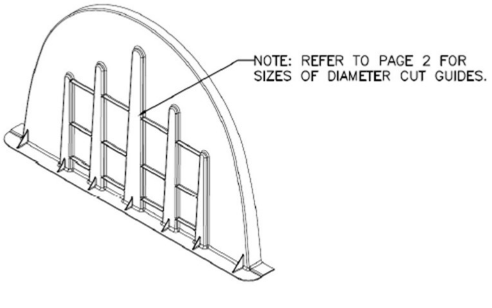

S-29 END CAP SPECS	
NOMINAL DIMENSIONS (LAYUP LENGTH X WIDTH X HEIGHT)	5.90" X 59.00" X 36.00" (150mm X 1499mm X 914mm)
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*MIN INSTALLED STORAGE	4.98 CUBIC FEET (0.141 CUBIC METERS)

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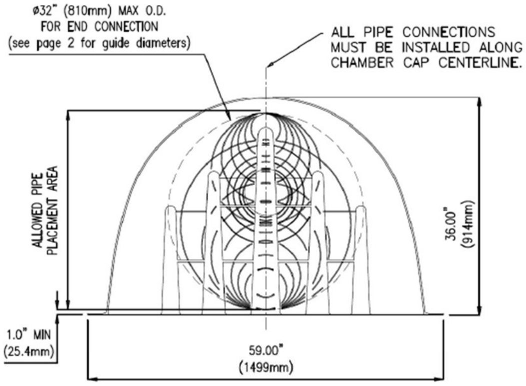

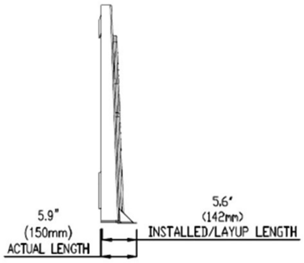

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S-29 CHAMBER END CAP DETAIL

TRITON - STANDARD DETAILS

PAGE 1 OF 2

REVISED:
02-26-16 JWM

TRITON S-29 PRODUCT SPECIFICATIONS

1.0 General

1.1 Triton chambers are designed to control stormwater runoff. As a subsurface retention or detention system, Triton chambers retain and allow effective infiltration of water into the soil. As a subsurface detention system, Triton chambers detain and allow for the metered flow of water to an outfall.

2.0 Chamber Parameters

2.1 The chamber shall be injection compression molded of a structural grade 1010 green soy resin composite to be inherently resistant to environmental stress cracking (ESCR), creep, and to maintain proper stiffness through temperature ranges of -40 degrees F to 180 degrees F.

2.2 The material property for the chamber and end cap must meet or exceed the following:
Tensile Strength- Ultimate: 21,755 PSI
Tensile Strength-Yield: 17,404 PSI
Tensile Modulus: 1,750-2,240 PSI
Flex Modulus: 1,600 KSI
Flex Yield Strength: 33,100 PSI
Compressive Strength: 30,457,000 PSI
Shear Strength: 11,500 PSI

2.3 The nominal chamber dimensions of the Triton S-29 shall be 36.0 inches tall, 59.0 inches wide and 35.0 inches long. Lay-up length is 33.35"

2.4 The chamber shall have an elliptical curved section profile.

2.5 The chamber shall be open-bottomed.

2.6 The chamber shall incorporate an overlapping corrugation joint system to allow chamber rows to be constructed.

2.7 The nominal storage volume of a Triton S-29 chamber shall be 41.06 cubic feet per chamber when installed per Triton's typical details. This equates to 2.67 cubic feet of storage/square foot of bed. This does not include perimeter stone.

2.8 The chamber shall have both of its ends open to allow for unimpeded hydraulic flows and visual inspections down a row's entire length.

2.9 The chamber shall have five corrugations to achieve strengths defined above.

2.10 The chamber shall have five circular and elliptical, indented and raised, surfaces on the top to the chamber for a maximum of 33 inch diameter optional top feed inlets, inspection ports and or clean-out access ports.

2.11 The chamber shall have 5 elliptical, indented, surfaces on either side of the chamber for optional feed inlets, outlets. Capable of accepting pipe O.D. up to 18 inches.

2.12 The chamber shall be analyzed, designed and field tested using AASHTO LRFD bridge design specifications 1. Design live load shall meet or exceed the AASHTO HS30 or a rear axle load of 48,000 pounds. Design shall consider earth and live loads <u>without</u> pavement as appropriate for the minimum of 18" of total cover to a maximum total cover of 50'.

2.13 The chamber shall be manufactured in an ISO 9001:2008 certified facility

2.14 The service life of the product is over 60 years under a constant sustained load of 10,000 PSI which is equal to the H-20 loading condition. Under typical loading conditions the Chamber and End Cap has a useful lifespan of 120 years from date of when manufactured.

2.15 Designed to exceed ASTM F2418, F2787, F2922 standard and AASHTO LRFD Bridge specifications. Validated through independent third party performance testing.

3.0 End Cap Parameters

3.1 The end cap shall be Injection Compression molded of 1010 green soy resin to be inherently resistant to environmental stress cracking (ESCR), creep and to maintain proper stiffness through temperature ranges of -40 degrees F to 180 degrees F.

3.2 The end cap shall be designed to fit over the last corrugation of a chamber, which allows: the capping of each end of the chamber row.

3.3 The end cap shall have six upper saw guides capable of accepting pipe O.D. up to 18.2" Six middle saw guides and eight lower saw guides capable of accepting pipe O.D. up to 28.2" to allow easy cutting for various diameters of pipe that may be used to inlet or outlet the system.

3.4 The end cap shall have excess structural adequacies to allow cutting an orifice of any size at any invert elevation.

3.5 The primary face of an end cap shall have 5 corrugations and be angled outward to resist horizontal loads generated near the edges of beds.

3.6 The end cap shall be manufactured in an ISO 9001:2008 certified facility.

3.7 The service life of the product to be over 60 years under a sustained load of 10,000 PSI which is equal to the H-20 loading condition.

4.0 Installation

4.1 Installation shall be in accordance with the latest Triton Installation manual that can be downloaded from the Triton website: www.tritonsws.com/support/downloads

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S-29 PRODUCT SPECIFICATIONS

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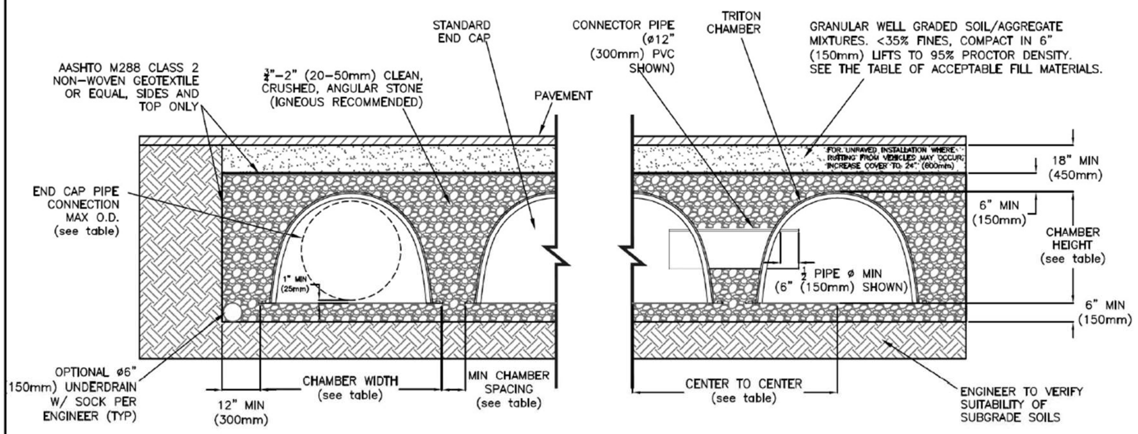

	CHAMBER WIDTH	CHAMBER SPACING	CENTER TO CENTER	CHAMBER HEIGHT	MAX END CAP O.D. CONNECTION	MAX SIDE O.D. CONNECTION	MAX TOP O.D. CONNECTION
S29	59" (1499mm)	6.0" (150mm) *7.5" (190mm)	65.0" (1651mm) *66.5" (1690mm)	36" (914mm)	32" (810mm)	18" (450mm)	24" (600mm)
S22	55" (1397mm)	6.0" (150mm)	61.0" (1549mm)	35" (889mm)	30" (760mm)	18" (450mm)	24" (600mm)
C10	39.7" (1008mm)	6.0" (150mm)	45.7" (1161mm)	25" (635mm)	20" (500mm)	12" (300mm)	18" (450mm)
M6	33.6" (853mm)	6.0" (150mm)	39.6" (1006mm)	17.5" (445mm)	14" (350mm)	8" (200mm)	12" (300mm)

*7.5" (190mm) SPACING OF DISTRIBUTION ROWS IS REQUIRED ONLY WHEN A PERPENDICULAR MAIN HEADER ROW IS USED. IF AN INLINE MAIN HEADER ROW IS USED, THEN MIN SPACING CAN BE 6" (150mm)

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CHAMBER CROSS SECTION
INFILTRATION

TRITON - STANDARD DETAILS

REVISED:
03-07-17 JWM

APPENDIX B. SUPPLEMENTARY TABLES

Table 2.1.5-1 Runoff Curve Numbers[1]

Cover description		**Curve numbers for hydrologic soil groups**			
Cover type and hydrologic condition	*Average percent impervious area*[2]	A	B	C	D
Cultivated land: without conservation treatment		72	81	88	91
with conservation treatment		62	71	78	81
Pasture or range land: poor condition		68	79	86	89
good condition		39	61	74	80
Meadow: good condition		30	58	71	78
Wood or forest land: thin stand, poor cover		45	66	77	83
good cover		25	55	70	77
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]					
Poor condition (grass cover <50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm drains (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Urban districts:					
Commercial and business	85%	89	92	94	95
Industrial	72%	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65%	77	85	90	92
1/4 acre	38%	61	75	83	87
1/3 acre	30%	57	72	81	86
1/2 acre	25%	54	70	80	85
1 acre	20%	51	68	79	84
2 acres	12%	46	65	77	82
Developing urban areas and Newly graded areas (pervious areas only, no vegetation)		77	86	91	94

[1] Average runoff condition, and $I_a = 0.2S$

[2] The average percent impervious area shown was used to develop the composite CNs. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. If the impervious area is not connected, the SCS method has an adjustment to reduce the effect.

[3] CNs shown are equivalent to those of pasture. Composite CNs may be computed for other combinations of open space cover type.

Table 3.1.5-2 Roughness Coefficients (Manning's n) for Sheet Flow[1]

Surface description		n
Smooth surfaces (concrete, asphalt, gravel, or bare soil):		0.011
Fallow (no residue):		0.05
Cultivated soils:	Residue cover <20%	0.06
	Residue cover >20%	0.17
Grass:	Short grass prairie	0.15
	Dense grasses[2]	0.24
	Bermuda grass	0.41
Range (natural):		0.13
Woods[3]:	Light underbrush	0.40
	Dense underbrush	0.80

[1] The n values are a composite of information by Engman (1986).

[2] Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.

[3] When selecting n, consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

Source: NRCS TR-55, TR-55, Second Edition, June 1986.

Table A-2
Atlanta

		Return Period						
		1	2	5	10	25	50	100
	n	0.75129	0.8542	0.7846	0.7768	0.7475	0.7519	0.7378
	a	35.11	66.20	62.28	69.74	72.79	83.83	87.36
	b	7	12	12	13	13	14	14
Hours	Minutes	Rainfall Intensity						
0.08	5	5.43	5.89	6.74	7.38	8.39	9.16	9.95
	6	5.11	5.61	6.45	7.08	8.06	8.81	9.58
	7	4.84	5.35	6.18	6.80	7.75	8.50	9.24
	8	4.59	5.12	5.94	6.55	7.48	8.20	8.93
	9	4.37	4.91	5.71	6.32	7.22	7.93	8.64
	10	4.18	4.72	5.51	6.10	6.99	7.68	8.38
	11	4.00	4.55	5.32	5.91	6.77	7.45	8.13
	12	3.84	4.38	5.15	5.72	6.56	7.24	7.90
	13	3.70	4.23	4.98	5.55	6.37	7.03	7.68
	14	3.57	4.09	4.83	5.39	6.20	6.84	7.48
0.25	15	3.44	3.96	4.69	5.24	6.03	6.67	7.28
	16	3.33	3.84	4.56	5.10	5.87	6.50	7.10
	17	3.23	3.73	4.44	4.97	5.73	6.34	6.93
	18	3.13	3.62	4.32	4.84	5.59	6.19	6.77
	19	3.04	3.52	4.21	4.72	5.46	6.05	6.62
	20	2.95	3.43	4.11	4.61	5.33	5.91	6.48
	21	2.87	3.34	4.01	4.51	5.22	5.79	6.34
	22	2.80	3.26	3.92	4.41	5.10	5.67	6.21
	23	2.73	3.18	3.83	4.31	5.00	5.55	6.09
	24	2.66	3.10	3.74	4.22	4.90	5.44	5.97
	25	2.60	3.03	3.66	4.13	4.80	5.33	5.85
	26	2.54	2.96	3.59	4.05	4.71	5.23	5.75
	27	2.48	2.90	3.52	3.97	4.62	5.14	5.64
	28	2.43	2.83	3.45	3.90	4.53	5.05	5.54
	29	2.38	2.77	3.38	3.82	4.45	4.96	5.45
0.50	30	2.33	2.72	3.32	3.75	4.38	4.87	5.36
	31	2.28	2.66	3.26	3.69	4.30	4.79	5.27
	32	2.24	2.61	3.20	3.62	4.23	4.71	5.18
	33	2.20	2.56	3.14	3.56	4.16	4.64	5.10
	34	2.16	2.52	3.09	3.50	4.09	4.56	5.02
	35	2.12	2.47	3.04	3.45	4.03	4.49	4.95
	36	2.08	2.43	2.99	3.39	3.97	4.43	4.87
	37	2.05	2.38	2.94	3.34	3.91	4.36	4.80
	38	2.01	2.34	2.89	3.29	3.85	4.30	4.73
	39	1.98	2.30	2.85	3.24	3.80	4.24	4.67
	40	1.95	2.27	2.81	3.19	3.74	4.18	4.60
	41	1.92	2.23	2.76	3.15	3.69	4.12	4.54
	42	1.89	2.19	2.72	3.10	3.64	4.06	4.48
	43	1.86	2.16	2.68	3.06	3.59	4.01	4.42
	44	1.83	2.13	2.65	3.02	3.54	3.96	4.37
0.75	45	1.80	2.09	2.61	2.98	3.50	3.91	4.31
	46	1.78	2.06	2.58	2.94	3.45	3.86	4.26
	47	1.75	2.03	2.54	2.90	3.41	3.81	4.21
	48	1.73	2.00	2.51	2.86	3.37	3.76	4.16
	49	1.71	1.98	2.48	2.83	3.33	3.72	4.11
	50	1.68	1.95	2.44	2.79	3.29	3.68	4.06
	51	1.66	1.92	2.41	2.76	3.25	3.63	4.02
	52	1.64	1.90	2.38	2.72	3.21	3.59	3.97
	53	1.62	1.87	2.35	2.69	3.18	3.55	3.93
	54	1.60	1.85	2.33	2.66	3.14	3.51	3.88
	55	1.58	1.82	2.30	2.63	3.11	3.47	3.84
	56	1.56	1.80	2.27	2.60	3.07	3.44	3.80
	57	1.54	1.78	2.25	2.57	3.04	3.40	3.76
	58	1.53	1.76	2.22	2.54	3.01	3.36	3.72
	59	1.51	1.74	2.20	2.52	2.98	3.33	3.69
1	60	1.49	1.72	2.17	2.49	2.95	3.30	3.65
2	120	0.96	1.14	1.40	1.58	1.84	2.02	2.21
3	180	0.68	0.81	1.01	1.14	1.32	1.46	1.61
6	360	0.39	0.48	0.60	0.69	0.80	0.90	0.97
12	720	0.23	0.28	0.36	0.41	0.47	0.53	0.58
24	1440	0.14	0.17	0.20	0.23	0.27	0.30	0.33

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